Conference on Nonlinear Systems and Dynamics

CNSD 2026

7th-10th July 2026, IISER Thiruvananthapuram, India

Invited Speakers

- Jürgen Kurths, PIK, Germany
- Stefano Boccaletti, CNR-ISC, Italy
- Eckehard Schöll, TU Berlin, Germany
- Rajarshi Roy, Univ. Maryland, USA
- Peter Ashwin, Univ. Exeter, UK
- Ulrike Feudel, Univ. Oldenburg, Germany
- Miguel AF Sanjuán, URJC, Spain
- Reik Donner, Magdeburg-Stendal UAS, Germany
- Boris Malomed, Tel Aviv Univ., Israel
- Sandip George, Univ. Aberdeen, UK
- Aasifa Rounak, Univ. College Dublin, Ireland
- Andrew Pickering, URJC, Spain
- Pilar Ruiz Gordoa, URJC, Spain
- Tomasz Kapitaniak, TUL, Poland
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- Anirban Banerjee, IISER Kolkata
- Anuradha Bhat, IISER Kolkata
- Deb Shankar Ray, IACS Kolkata
- Chandrasekar V. K., SASTRA Univ., TN
- Pushpita Ghosh, IISER TVM
- Vasantha J. Raja, SASTRA Univ., TN
- Nithyanandan K., IIT Hyderabad
- Sangeeta Ujjwal, BHU, Varanasi
- Chandrakala Meena, IISER Pune
- Ravi Pant, IISER TVM
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- Solingyur Zimik, IISER TVM
- Dr. Nivedita Deo, University of Delhi
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CAMPUS MAP

1 Campus Entrance
2 **Visitors' Forest Retreat (VFR)**
3 Students' Library
4 ATM
5 Restaurant
6 Bus Stop
7 **Central Dining Hall - I**
8 Student Lounge and Cafe
9 **Physical Sciences Block**
10 Chemical Sciences Block
11 Biological Sciences Block
12 School of Earth, Environmental and Sustainability Sciences (SEESS)
13 Mathematics Sciences Block
14 Shopping Center
15 Animal House Block
16 **Lecture Hall Complex**
17 Crucible (Student Activity Centre)
18 **Students' Hostel area**
19 Medical Center
20 Playground Area
21 Administrative complex
22 **Central Dining Hall - III**

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Invited Talks

CNSD 2026

Mechanical systems with discontinuities, time-delay effects and noise

Meiyazhagan Jaganathan[1], Dan McKeagney[1], Louis Kelleher[1], Aasifa Rounak[1]

[1]UCD Centre for Mechanics, Dynamical Systems and Risk Laboratory

Mechanical systems often operate under conditions where discontinuities, time-delays, and stochastic perturbations interact to produce complex dynamical behaviour [1].

The discontinuities inherent in these systems give rise to strong nonlinearities that cannot, in general, be regularised or smoothed without altering the essential dynamics, leading to behaviour that is markedly more complex than that of smooth nonlinear systems. Discontinuities may arise from impacts, friction, backlash, while time delays are commonly introduced through control feedbacks, regenerative effects in machining, or material and process memory. In practical systems, these mechanisms rarely occur in isolation and are often further influenced by noise arising from fluctuating system coefficients or external excitations. Such interacting complexities can give rise to rich dynamical phenomena, including multistability, noise-induced basin hopping, chatter-like instabilities, and, in systems exhibiting sliding motion, loss of predictability near switching boundaries. Understanding these combined effects is therefore essential for characterising the phenomenological behaviour of such systems [2].

The first problem examined in this study is the dynamics of high-speed handheld surgical micro-drills used in neurosurgical applications. A typical setup for a controlled surgical drill is shown in Fig. 1. During cutting, the interaction between the rotating bur and the bone substrate forms a complex nonlinear mechanical process characterised by intermittent contact, modulation of cutting forces due to the anisotropic and heterogeneous nature of the tissue being cut, and geometry-dependent structural excitation. In particular, axisymmetric and non-axisymmetric bur geometries can give rise to distinct modal characteristics: while axisymmetric burs tend to concentrate the response around a dominant bending mode, tapered non-axisymmetric burs may excite multiple closely spaced competing modes, producing amplitude modulation and beating, leading to cutting-induced instabilities, called chatter. Experimental investigations, together with the development of a preliminary mathematical model, will be presented, and the mechanisms underlying the emergence of chatter will be discussed.

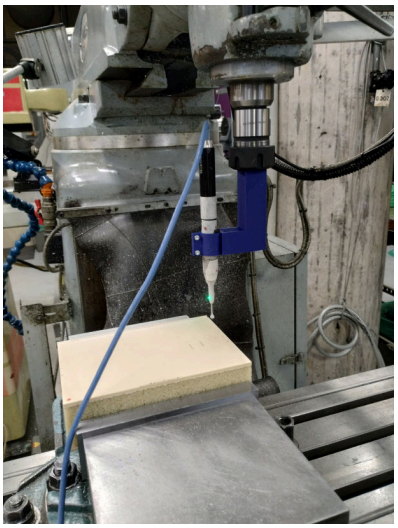

Figure 1: The setup of a controlled surgical bur test.

The second problem focuses on vibration mitigation using a double-impacting vibro-impact and frictional nonlinear energy sink. In this study, it was shown that a vibro-impact nonlinear energy sink, with a mass ratio of 0.066, could achieve an approximately by approximately two-thirds relative to the uncontrolled case, demonstrating its potential as an effective passive vibration-control strategy.

Together, the two problems highlight how complex nonlinear interactions can generate undesirable vibrations in some applications, while being deliberately exploited for vibration suppression in others.

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Non-commutative Painlevé hierarchies

Andrew Pickering

Área de Matemática Aplicada, Universidad Rey Juan Carlos, Madrid, Spain

The question of obtaining analogues of the Painlevé equations, having properties that mirror those of the Painlevé equations themselves, is a topic that has been of interest for some considerable time now. In particular, the derivation of sequences of such ordinary differential equations, of increasing order, that is, of so-called Painlevé hierarchies, is a subject that has attracted significant attention. In this regard, use is made of the well-known connection with completely integrable systems. However, the underlying structures of integrable systems have also been shown to play a crucial role in extracting information about the properties of the Painlevé hierarchies thus obtained. Important properties include Lax pairs, auto-Bäcklund transformations and special integrals.

In this talk we will concentrate on Painlevé equations and hierarchies involving non-commuting variables, whether matrix-valued or taking values in an associative algebra. We present recent results for such systems. Amongst other examples, we present a new matrix second Painlevé hierarchy, along with a corresponding new Schwarzian matrix second Painlevé hierarchy. Still further extensions of the known matrix second Painlevé hierarchy are also given.

In the above, it is worth highlighting the discovery of a new definition of matrix Schwarzian derivative. We give proofs of some of its basic properties. Fundamental to the approach used here is the use of auto-Bäcklund transformations, but now between mathematical quantities rather than differential equations.

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[2] A. Pickering, *A new approach to deriving Bäcklund transformations*, J. Math. Anal. Appl. **544** (2025), 129052.

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Understanding environmental and climatic factors driving fish stream communities in Indian hill-stream ecosystems: a predictive modelling approach

Anuradha Bhat

Department of Biological Sciences, IISER Kolkata, India

Freshwater fish communities exhibit substantial variation across spatial scales, shaped by environmental filtering and dispersal limitation. However, the relative contribution of these processes remains insufficiently understood, particularly along subtropical elevational gradients. Species traits may improve predictions of ecological niches and co-occurrence patterns, potentially enabling broader ecological generalisations across ecosystems. In this study, we modelled fish species occurrences as a function of environmental variables and spatial distance to evaluate the influence of traits and phylogeny on species niches and patterns of co-occurrence. We also assessed the consistency of these relationships across river basins.

As a case study using fish community data collected over multiple years from the Teesta-Jaldhaka river basins of the Eastern Himalayas, we used a predictive modelling approach and fitted joint species distribution models (JSDMs). Environmental filtering exerted a stronger influence on species occurrence than spatial distance. Elevation, total dissolved solutes, dissolved oxygen, and stream width accounted for substantial variation in species distributions, although their relative importance varied between basins. Species traits explained comparatively less variation in niches and co-occurrence patterns, and their effects were basin-specific. Nonetheless, residual phylogenetic signals in species niches suggest that unmeasured traits may have an important influence.

Our findings indicate that environmental filtering is the dominant process structuring lotic fish communities along subtropical elevational gradients in adjacent Eastern Himalayan river basins. However, differences in the strength of environmental drivers and trait-niche relationships among basins complicate broad ecological generalisations across freshwater systems, while also highlighting opportunities to test the applicability of ecological filtering frameworks in other riverine ecosystems.

Trotter Transition in BCS Pairing Dynamics

Aniket Patra[1], Emil A. Yuzbashyan[2], Boris L. Altshuler[3], Sergej Flach[4,5]

[1]Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India
[2]Department of Physics and Astronomy, Center for Materials Theory, Rutgers University, Piscataway, NJ 08854, USA
[3]Physics Department, Columbia University, 538 West 120th Street, New York, NY 10027, USA
[4]Center for Theoretical Physics of Complex Systems, Institute for Basic Science, Daejeon 34126, Republic of Korea
[5]Basic Science Program, Korea University of Science and Technology (UST), Daejeon, 34113, Republic of Korea

Introduction and Motivation: We investigate how time discretization — via Trotterization or equivalently symplectic integrators — affects the dynamics of the integrable reduced BCS model [1]. In both classical computation and digital quantum simulation, complex Hamiltonians are approximated by splitting them into solvable pieces, evolving under each, and recombining. While exact in the continuum limit, finite step sizes can generate artificial dynamics, sometimes chaotic. Earlier studies showed that symplectic integration can induce chaos in integrable systems like the Toda chain [2]. Here, the authors extend this line of study to the mean-field reduced BCS Hamiltonian.

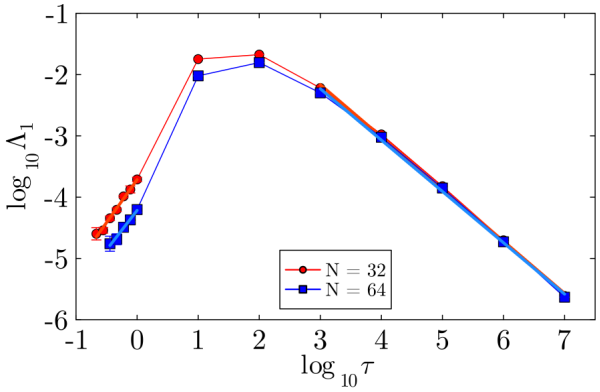

Figure 1: We show $\log_{10}\Lambda_1$ as a function of $\log_{10}\tau$ for $N = 32$ and 64. We have included the error bars. For a fixed N, we choose a configuration where all the spins point in random directions. In the memoryless regime, the N dependence of Λ_1 is quite weak.

The central discovery is a Trotter transition: as the Trotter step τ grows, the system undergoes a dynamical shift from weak chaos (perturbed integrability) to strong, memoryless chaos. This transition parallels quantum chaos observed in digital simulations and shares features with paradigmatic chaotic systems like the kicked top.

The Reduced BCS Model and Trotterization: The reduced BCS Hamiltonian,

$$\hat{H}_{\rm BCS} = \sum_{j=1}^{N} \varepsilon_j (\hat{c}^\dagger_{j\uparrow}\hat{c}_{j\uparrow} + \hat{c}^\dagger_{j\downarrow}\hat{c}_{j\downarrow}) - g \sum_{j,q=1}^{N} \hat{c}^\dagger_{j\uparrow}\hat{c}^\dagger_{j\downarrow}\hat{c}_{q\downarrow}\hat{c}_{q\uparrow}, \tag{1}$$

describes Cooper pairing between time-reversed states. Using Anderson pseudospins: $\hat{S}^z_j = (\hat{c}^\dagger_{j\uparrow}\hat{c}_{j\uparrow} + \hat{c}^\dagger_{j\downarrow}\hat{c}_{j\downarrow} - 1)/2$ and $\hat{S}^-_j = (\hat{S}^+_j)^\dagger = \hat{c}_{j\downarrow}\hat{c}_{j\uparrow}$, the model maps to a system of N classical spins under mean-field approximation: $\hat{\boldsymbol{S}}_j \to \boldsymbol{S}_j$. Both the quantum and mean-field forms are integrable.

To implement symplectic integration, the Hamiltonian is split into two parts:

$$H_{\rm BCS} = \underbrace{\sum_{j=1}^{N} 2\varepsilon_j S^z_j}_{H_{\rm free}} \underbrace{- g \sum_{j,k=1}^{N} S^+_j S^-_k}_{H_{\rm int}} \equiv H_{\rm free} + H_{\rm int}. \tag{2}$$

with each piece exactly solvable as rotations of spins. The SABA2 integrator — which is second order with a precision of $\mathcal{O}(\tau^3)$ in the single-step time evolution operator $e^{\tau L}$, where τ is the step size and L is the Liouvillian operator — is employed to evolve the system, mimicking Suzuki-Trotter decompositions in quantum simulation.

Diagnostic Tools — Lyapunov Spectra and Entropy: Chaos is quantified via Lyapunov characteristic exponents (LCEs). These measure exponential growth rates of infinitesimal deviations, obtained from the variational equations of motion. The Lyapunov spectrum encodes the full set of exponents, while the maximum Lyapunov exponent (mLCE) Λ_1 (Fig. 1) signals chaos if positive. Another diagnostic is the Kolmogorov–Sinai (KS) entropy (Fig. 2), the sum of positive exponents per degree of freedom, which quantifies information production.

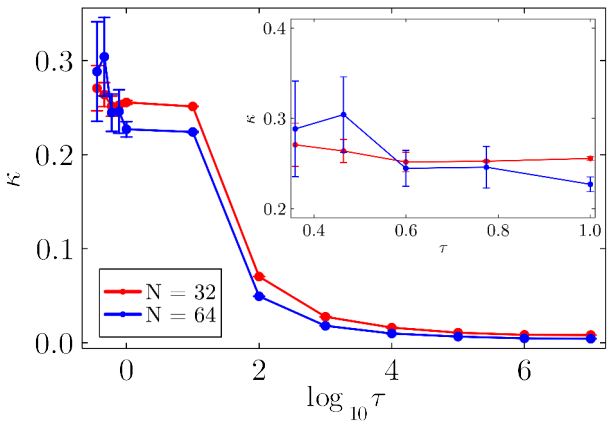

Figure 2: We show the rescaled Kolmogorov-Sinai entropy κ as a function of $\log_{10}\tau$ for $N = 32$ and 64. In the inset, we show a magnified κ versus τ plot for the small τ long-range network regime.

The analysis reveals distinct scaling behaviors for Λ_1 with τ — see Fig. 1:

- *Small τ (near integrability):* We have $\Lambda_1 \propto \tau^{\eta}$ where $\eta = 1.40 \pm 0.06$ for $N = 32$ and $\eta = 1.29 \pm 0.09$ for $N = 64$. Weak chaos emerges due to long-range coupling between action variables (long-range network class).
- *Large τ (memoryless chaos):* In the memoryless regime, we obtain $\eta = -0.85 \pm 0.02$ both for $N = 32$ and $N = 64$. Dynamics become strongly chaotic with short temporal correlations, akin to ergodic random maps.

The rescaled Kolmogorov-Sinai entropy, shown in Fig. 2, mirrors this transition: saturating at finite values in the weakly chaotic regime, but dropping sharply in the memoryless regime.

Analytical Insights and Connection to the Kicked Top: A remarkable feature is that in the large τ regime, the dynamics map onto the well-studied kicked top. For $N = 2$ with particle-hole symmetry, the SABA2 map reduces to iterations of a kicked top Hamiltonian. This allows an analytical scaling law:

$$\tau\Lambda_1 \approx 2\ln\left(\tau/\sqrt{N}\right) + C_N, \tag{3}$$

where C_N is a τ independent constant. This is valid only when $\tau/\sqrt{N} \gg 1$. This explains the observed universal scaling and weak N-dependence in the chaotic regime. From this, the critical step size for the transition is estimated as $\tau_c \sim \sqrt{N}$ in excellent agreement with numerics.

Conclusion and Broader Implications: This paper demonstrates that time discretization itself can induce chaos in an integrable many-body model, leading to a Trotter transition governed by universal scaling. The reduced BCS model provides a clean, compact phase-space setting where both weak and strong chaos can be systematically analyzed. The interplay between symplectic integrators, Lyapunov spectra, and mapping to the kicked top reveals deep connections between numerical methods, classical chaos, and quantum simulation. These insights are not only of theoretical importance but also crucial for understanding the reliability of digital quantum simulators and classical integrators in many-body physics.

For digital quantum computers, Trotter errors, and chaotic instabilities may follow similar scaling laws. The reduced BCS model's all-to-all interactions make it relevant for near-term quantum devices with global connectivity. Future directions include studying disorder, noise, and different integrators, as well as exploring nonlocal observables such as entanglement entropy and the Loschmidt echo, where mean-field theory breaks down.

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Study of synchronisation in multibody interactions using hypergraphs

Anirban Banerjee[1], Samiron Parui[1,2]

[1]IISER Kolkata, Mohanpur, India
[2]IISER Bhopal, Bhopal, India

We propose a framework for modelling multi-body interactions in dynamical networks using hypergraphs as the underlying interaction structure. This approach generalises conventional network models based solely on pairwise interactions. To capture the higher-order interaction patterns, we introduce a class of matrices associated with weighted hypergraphs, allowing interactions of varying strengths. The resulting framework is employed to study both global and local synchronisation in discrete- and continuous-time dynamical networks.

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Designs and efficient means of creating quantum chaos

Arul Lakshminarayan[1]

[1]Department of Physics, Indian Institute of Technology Madras, Chennai 600036, India

Random numbers are typically psuedorandom numbers arising from deterministic protocols and chaotic systems. Similarly quantum chaos gives rise to unitaries and states that are psuedorandom. The ideal random being the Haar measure: uniform measure on the set of states or the set of unitary operators. Questions about randomness of quan- tum chaotic states and propagators are thus made in comparison with the Haar measure. Quantum state and unitary $t-$designs are a graded approach to the Haar measure. We explore simple quantum chaotic systems both in the light of quantum state and unitary $t-$designs. While Haar random unitaries and states play a key role in many quantum protocols, including private channels, data hiding and decoupling, they are not efficiently generated on a quantum computer. On the other hand, it is known that quan- tum chaotic systems are simulable efficiently and are hence a good resource for pseudo-random states and operators. For example, the quantum stan- dard map of dimension 2n is simulable with n3 two- qubit gates. We show how to use the well-known quantum Fourier transform and efficiently generate approximate t-designs using only O(n2) two-qubit gates, using again simple models of deterministic chaos.

One Parameter Family of Elliptic Plane Pendulum Equations

Avinash Khare

Physics Department, Savitribai Phule Pune University, Pune 411007, India

We introduce one parameter family of elliptic plane pendulum equations in terms of Jacobi elliptic function $-\mathrm{sn}(\theta, m)/\mathrm{dn}(\theta, m)$ which smoothly goes over to the plane pendulum equation in the $m = 0$ limit and the hyperbolic plane pendulum equation in the $m = 1$ limit where m is the modulus of the Jacobi elliptic functions[cite: 161]. We show that in the harmonic approximation, the entire family of elliptic pendulum problems characterized by $0 \leq m \leq 1$ represents one parameter family of isochronous system[cite: 162]. Further, we show that unlike the plane pendulum, the elliptic pendulum with $m = 1/2$ continues to be an isochronous system even in the first anharmonic approximation[cite: 163]. Besides, we also obtain several exact hyperbolic and periodic solutions of the entire elliptic pendulum family in the first and the second anharmonic approximation[cite: 164]. For each of the periodic solution we also mention the corresponding time period[cite: 165]. Finally we obtain novel connection between the exact solutions of the plane pendulum, the hyperbolic plane pendulum and the inverted plane pendulum equations as well as the static solutions of the Sine Gordon as well as the Sine hyperbolic Gordon equations and obtain few exact solutions of the above mentioned equations.

Multidimensional Solitons

Boris Malomed

Dept. of Physical Electronics School of Electrical Engineering Faculty of Engineering Tel Aviv University

It is commonly known that the interplay of linear and nonlinear effects gives rise to solitons, i.e., self-trapped localized structures, in a wide range of physical settings, including optics, Bose-Einstein condensates (BECs), hydrodynamics, plasmas, condensed-matter physics, etc. Nowadays, solitons are considered as an interdisciplinary class of modes, which feature diverse internal structures.

While most experimental realizations and theoretical models of solitons have been elaborated in one-dimensional (1D) settings, a challenging issue is prediction of stable solitons in 2D and 3D media. In particular, multidimensional solitons may carry an intrinsic topological structure in the form of vorticity. In addition to the "simple" vortex solitons, fascinating objects featuring complex structures, such as hopfions, i.e., vortex rings with internal twist, have been predicted too.

A fundamental problem is the propensity of multidimensional solitons to be unstable (naturally, solitons with a more sophisticated structure, such as vortex solitons, are more vulnerable to instabilities). Recently, novel perspectives for the creation of stable 2D and 3D solitons were brought to the attention of researchers in optics and BEC. The present talk aims to provide an overview of the main results and ongoing developments in this vast field. An essential conclusion is the benefit offered by the exchange of concepts between different areas, such as optics, BEC, and hydrodynamics.

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Gravity-Driven Eco-Epidemiological Dynamics in Tri-Trophic Food Chains

Yuvraj Singh Patil[1], **Chandrakala Meena**[1]

[1]Indian Institute of Science Education and Research, Pune, 411008, India

Despite significant advances in theoretical ecology, understanding ecosystem stability under realistic ecological processes remains a major challenge [1]. In particular, the combined influence of spatially dependent interactions and infectious diseases on multi-trophic food chains is still not well understood [2]. To understand how spatial interactions and infectious diseases jointly shape ecosystem dynamics we develop a gravity-based eco-epidemiological model for a tri-trophic food chain in which trophic interaction strength depends on species abundances and decreases with effective interaction distance (Fig. 1(a)). In the absence of infection, the system exhibits stable coexistence of all three trophic levels. Remarkably, introducing infection into the intermediate consumer population destabilizes this equilibrium through a Hopf bifurcation, giving rise to sustained oscillations in species abundances (Fig. 1(b,c)). We find that the infection-modulated predation parameter w plays a crucial role in controlling the persistence and amplitude of these oscillations. A phase diagram in the (β/γ)–G parameter space reveals distinct regions of stable coexistence and oscillatory dynamics, demonstrating how disease transmission and gravity-mediated interactions jointly govern ecological outcomes (Fig. 1(d)).

Extending the framework further, we investigate infection in the apex predator population and uncover a rich landscape of persistence and extinction regimes. In particular, we identify a critical gravity-coupling threshold G_c that separates predator survival from extinction across the $(\beta/\gamma, w)$ parameter space. Our results reveal that disease can fundamentally reshape trophic dynamics without necessarily causing ecosystem collapse, while gravity-driven interactions provide a powerful mechanism for regulating stability and persistence. These findings establish gravity-based eco-epidemiological models as a promising framework for understanding how spatial structure and disease processes interact to drive ecological resilience, oscillatory behaviour, and species survival.

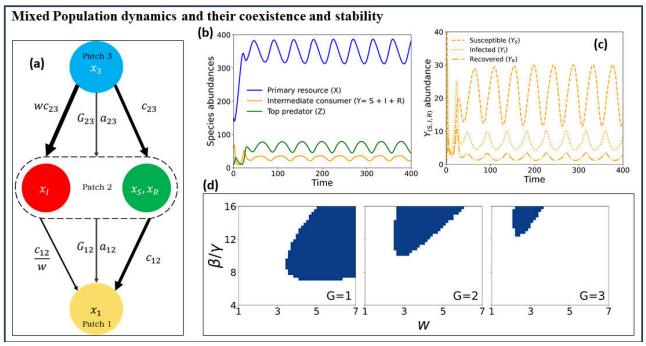

Figure 1: (a) Tri-trophic food chain system with gravity-based interactions and infection in the intermediate consumer (S, I, R). (b) Temporal evolution of all populations. (c) Epidemiological variables. (d) Phase diagram showing oscillatory region in the (β/γ)–w parameter space for varying gravity strength G.

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Two-time scale method for nonlinear stochastic equations

Deb Shankar Ray[1]

[1]Indian Association for the Cultivation of Science, Kolkata 700032, India

Nonlinear stochastic differential equations are extensively used in many problems of natural sciences. We make use of the Blekhmann perturbation method along with Lindstaedt-Poincare technique to solve these equations for direct calculation of the moments. An interesting offshoot of the treatment is to estimate the bound on the strength of noise to destabilize a noisy limit cycle. We intend to discuss these along with the other issues of diffusive dynamics.

Coherence Resonance in Excitable Systems and Networks

Eckehard Schöll

Technische Universität Berlin, Germany

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 in [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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Frustration induced chimeras and motion in two dimensional swarmalators

Gopal R

Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur – 613 401, Tamil Nadu, India

Swarmalators are oscillators that combine the properties of swarming systems and coupled oscillators, providing a framework to study systems where individual agents synchronize their internal states and simultaneously organize their spatial positions, making them potential candidates for replicating complex dynamical states. In this work, we explore the effects of a frustration parameter in the phase interaction functions of a two-dimensional swarmalator model inspired by the solvable Sakaguchi-swarmalators that move in a one-dimensional ring. The impact of the frustration parameter in these models has been a topic of great interest. Real-world coupled systems with frustration exhibit remarkable collective dynamical states, underscoring the relevance of this study. The frustration parameter induces various states exhibiting non- stationarity, chimeric clustering where swarmalators split into distinct groups that exhibit synchronized and unsynchronized behavior, both in their oscillatory phases and spatial positions, and global translational motion, where swarmalators move spontaneously in two-dimensional space. We investigate the characteristics of these states and their responses to changes in the frustration parameter. Notably, the emergence of chimeric states suggests the crucial role of non-stationarity in phase interactions for spontaneous population clustering. Additionally, we examine how phase non-stationarity influences the spatial positions of swarmalators and provide a classification of these states based on different order parameters.

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Symbol sequences from three-rotor coincidences and their word-complexity

Govind S. Krishnaswami[1], Anirudh Rameshan[2]

[1]Physics Department, Chennai Mathematical Institute, SIPCOT IT Park, Siruseri 603103, India
[2]UM-DAE Centre for Excellence in Basic Sciences, University of Mumbai, Vidyanagari, Mumbai 400098, India

In the three-rotor problem, three equally massive point particles move on a circle interacting via attractive pairwise cosine potentials. Rotors can represent superconducting phases of distinct metallic segments in a chain of coupled Josephson junctions. We propose a digitization of the classical dynamics that records successive pair and triple coincidences of rotors using four symbols. The conditions for rotor coincidences are expressed in terms of relative angles and correspond to the boundaries in a disjoint partition of the configuration torus into cells where the rotors are ordered clockwise and anticlockwise. It is shown that isolated rotor coincidences must be crossings. We study the symbol sequences and word statistics for classes of periodic, quasiperiodic and chaotic trajectories. Word-complexity C_n measures the diversity of n-letter words in the symbol sequence while topological entropy governs asymptotic growth of C_n. Periodic sequences have a word-complexity that saturates at the period. Ultra-high-energy trajectories with irrational 'slope' are quasiperiodic. For them, we show $C_n = n + 3$ by examining limiting slopes and by a mapping to Sturmian sequences. We examine their grammar rules and propose how their right-special words may be identified. Numerical investigation of symbol sequences of orbits from the band of global chaos leads us to conjecture an exponentially growing word-complexity $C_n = 3 \times 2^{n-1}$ corresponding to a topological entropy $\log 2$.

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Climate Meets Complex Systems Science: Exploring Extreme Climate Events via a Complex Network Approach

Jürgen Kurths[1]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany

The Earth system is a very complex and dynamical one basing on various feedbacks. This makes predictions and risk analysis even of very strong (sometime extreme) events as floods, landslides, heatwaves, and earthquakes etc. a challenging task.

A recently developed approach via complex networks will be presented. This leads to an inverse problem: Is there a backbone-like structure underlying the climate system? To treat this problem, we have proposed some methods to reconstruct and analyze a complex network from spatio-temporal data based on a nonlinear causality analysis. This approach enables us to uncover relations in the climate system even between far away tipping points as Amazonia and the Tibetan Plateau or Arctic and Southwest China, but also to follow-up rather short phenomena as tropical cyclones.

Then extreme events are studied from this perspective by means of the nonlinear event synchronization analysis. This way we discover relations to global and regional circulation patterns in oceans and atmosphere, which lead to construct substantially better predictions, in particular for the onset of the Indian Summer Monsoon, the Indian Ocean Dipole, or heat waves in Europe.

Logic From Nonlinear Dynamics

K. Murali[1]

[1]Anna University, Chennai, India

The exploration of alternative computational paradigms has resulted in the development of $chaogates$, which utilizes the intrinsic behaviors of nonlinear physical systems for universal computation. In contrast to traditional digital logic, which depends on synthesized linear components, dynamics-based logic leverages the complex, non-proportional outputs of nonlinear maps such as the logistic and tent maps to implement Boolean functions.

Historically, these implementations required multiple iterations of chaotic maps and complex multi-transistor circuits, which were prone to exponentially increasing errors and hardware overhead. Recent advancements simplify this framework by demonstrating that all binary Boolean functions can be realized through a single iteration of a simple nonlinear function. By partitioning the input space into distinct regions and evolving them through a nonlinear map, the output can be compared against a threshold to yield specific Boolean truth values.

Experimental validation using a single unijunction transistor (UJT) — a component with a single p-n junction — demonstrates that adjusting a single operating parameter (gate voltage) allows for on-the-fly morphing between six common logic gates: AND, NAND, OR, NOR, XOR, and XNOR. This single-component approach significantly reduces hardware complexity, enhances integration density, and improves energy efficiency. Furthermore, the discovery that these logic functions occupy open sets of parameters ensures robust operation against manufacturing imperfections and operational noise, establishing a practical foundation for next-generation, secure, and adaptive computation.

Fractional Order Chaos

M. Lakshmanan

Department of Nonlinear Dynamics, School of Physics, Bharathidasan University, Tiruchirappalli - 620024, Tamil Nadu.

Fractional-order dynamical systems (modeled by fractional order differential equations) are attracting significant attention due to their ability to incorporate memory effects and accurately model complex physical phenomena. In this talk, I will discuss some basic aspects of the dynamics of fractional-order (linear and) nonlinear oscillatory systems with increasing levels of complexity. I will first analyze the dynamics of linear harmonic and anharmonic fractional-order oscillators to understand the consequences of fractional order on their dynamical behavior. The study is then extended to damped and externally forced linear/nonlinear oscillators, including the Mathews-Lakshmanan and Duffing oscillator systems, where various dynamical phenomena such as bifurcations and chaos are explored as a function of the fractional order parameter. Finally, I will briefly discuss the dynamics of fractional-order coupled Rössler oscillators to appreciate the collective behavior and synchronization aspects in fractional-order chaotic systems. Numerical simulations will be used to characterize the dynamical states through phase portraits, bifurcation analysis, and other nonlinear diagnostics to bring out the role of fractional-order in shaping the dynamics of nonlinear and chaotic oscillatory systems.

Multiscale Order and Entropy in Music, Text, Genes, and Turbulence

Mahendra Verma

Department of Physics, Indian Institute of Technology Kanpur, Kanpur 208016, India

Thermodynamic entropy describes disorder at small scales, but it cannot capture the hydrodynamic order. For example, the thermodynamic entropy of Euler turbulence (with zero viscosity) is constant, even while the flow structures of the flow changes with time. The latter evolution is nicely captured by hydrodynamic or multiscale entropy, which is $-\sum_k p_k \log_2 p_k$ with $p_k = E(k)/\sum_k E(k)$ [1, 2]. Here, $E(k)$ is the energy spectrum. Figure 1 illustrates the evolution of hydrodynamic entropy of 3D and 2D Euler turbulence. We also show that the hydrodynamic entropy is not extensive because it is not proportional to the system size. Consequently, we cannot add hydrodynamic and thermodynamic entropies. The entropy of flow turbulence is between 3 and 4. We extended the above analysis to music, texts in various languages, and genes. The energy spectra of the time series of these systems exhibit power law and hydrodynamic entropy of $\mathcal{O}(1)$.

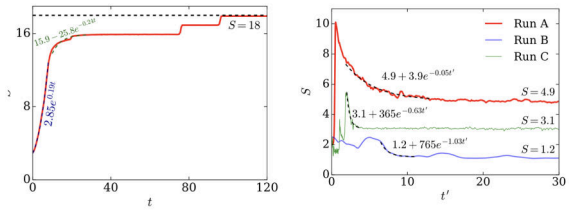

Figure 1: The time series of 3D Euler turbulence (left) and 2D Euler turbulence (right). The entropy increases in 3D, but decreases in 2D for a period of time. The latter signifies ordering of the 2D Euler flow.

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Reservoir Computing for the Prediction and Control of Complex Dynamics

Manish Dev Shrimali

Central University of Rajasthan, Ajmer 305 817, India

Reservoir Computing (RC), a paradigm of machine learning (ML), provides a robust and efficient framework for approximating the dynamics of complex systems by leveraging nonlinear information processing with minimal training requirements[cite: 130, 132, 133, 134]. The framework utilizes a fixed nonlinear dynamical system, often referred to as a reservoir, to map low-dimensional input signals into a high-dimensional feature space[cite: 134, 137]. In recent years, RC has demonstrated remarkable capability in capturing temporal dynamics, reconstructing underlying attractors, predicting the collective behavior of oscillators in networks from limited data, and learning the coupling structure between interacting oscillators[cite: 138, 139, 141, 143, 144, 145]. Its computational efficiency and reduced training complexity make it particularly attractive for real-time analysis of high-dimensional nonlinear systems[cite: 145, 148].

Furthermore, RC offers a powerful data-driven alternative when accurate first-principles models are unavailable or computationally prohibitive[cite: 148, 149]. These advantages have motivated growing interest in employing RC to uncover latent dynamical structures and to facilitate model-free control strategies in complex systems[cite: 149, 152]. In addition to its success in predicting complex dynamical behaviors, RC has recently been employed for controlling dynamical systems[cite: 152, 153]. A data-driven framework for the adaptive control of dynamical systems has been demonstrated by leveraging the RC scheme[cite: 154, 156]. RC has been extensively applied to the data-driven modeling and prediction of complex nonlinear dynamical systems across climate science, neuroscience, and engineering applications[cite: 156].

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Vibrational Resonance: Recent Advances and Applications

Miguel A. F. Sanjuán[1]

[1]Nonlinear Dynamics, Chaos and Complex Systems Group, Departamento de Física,
Universidad Rey Juan Carlos, Tulipán s/n, 28933 Móstoles, Madrid, Spain
[1]Royal Academy of Sciences of Spain, Valverde 22, 28004 Madrid, Spain

Over the past two decades, vibrational resonance has emerged as a key phenomenon in nonlinear dynamics, garnering significant attention across physics, biology, neuroscience, engineering, and beyond. Vibrational resonance involves the amplification of a faint characteristic signal through the constructive interplay of a nonlinear system and an auxiliary high-frequency excitation. This talk will explore the foundations of vibrational resonance, including characteristic signals and nonlinear models, providing a comprehensive overview of the metrics used for its quantification. We will also present recent theoretical advances, encompassing direct separation of motions, ultrasensitive vibrational resonance, and the role of noise. In addition, two practical applications such as image processing and fault diagnosis will be showcased to demonstrate the utility of vibrational resonance in real-world scenarios. This presentation aims to provide an accessible yet thorough examination of vibrational resonance, encouraging further research into its theoretical and engineering aspects.

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Extreme events of quantum walks on networks

M. S. Santhanam

Indian Institute of Science Education and Research, Pune, India 411008.

For classical random walks on networks, the flux-fluctuation relation is an important characteristic that relates the mean flux and strength of fluctuations on the nodes. It was extensively studied before, although equivalent relations for quantum walks on networks remain unknown. In this talk, we present a quantum version of the flux-fluctuation relation, and its application to defining and studying extreme events. It is valid for quantum walks on an arbitrary network, subject to the condition that the spectrum of the unitary walk operator is nondegenerate. Remarkably, for phase coherent quantum walks, the quantum flux-fluctuation relation is qualitatively similar to its classical counterpart, and quantum effects are insignificant. The numerically simulated quantum walks on periodic lattices and scale-free and Erdős-Rényi networks are consistent with the analytical quantum flux-fluctuation relation [1].

In the second part of the talk, we discuss extreme events generated by quantum walks. Extreme events are the ones for which the magnitude of the event is much larger than its typical values. They have been extensively investigated on classical dynamical and stochastic processes on networks. Due to unitary quantum evolution, the quantum walk dynamics usually differs from that of the classical random walks, and hence we expect extreme event properties to be different in classical and quantum settings. In contrast to this expectation, we show that extreme events of phase coherent quantum walks are qualitatively similar to that of classical random walks. We show that this counterintuitive behavior originates from the dominance of nodal fluctuations over internode correlations in disordered network structures. In particular, the occurrence probability for extreme events on scale-free and Erdős-Rényi networks displays a decaying power law with the degree of nodes. That is, the extreme event probability is larger for small degree nodes compared to the hubs on the network, in qualitative agreement with corresponding classical random walk results [2].

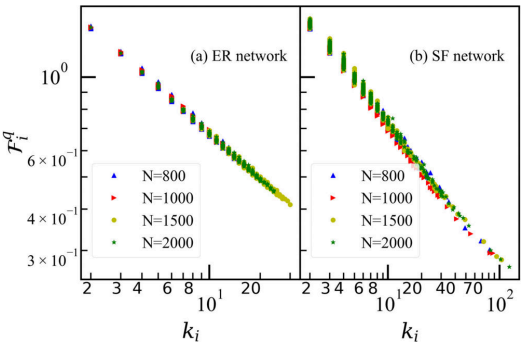

Figure 1: Extreme event occurrence probability as a function of degree k for discrete time quantum walks on Erdos-Reyni and Scale-free networks.

Finally, we also discuss some novel properties of lackadaisical quantum walks on networks. By analytically calculating the mean walker position, we demonstrate the existence of two distinct scaling regimes for walks on a line and on a binary tree. By tuning the initial state, the dynamics of the quantum walker can be manipulated. If time permits, we will demonstrate its application for a quantum algorithm [3].

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Beyond Dark-Bright Solitons: Higher-Order Bright–Dark Soliton Complexes in an NPR Fiber Laser

Subrata Manna[1], Amala Jose[1], Nithyanandan Kanagaraj[1]

[1]Ultrafast Fiber Optics and Smart Photonics Technology Lab, Department of Physics, IIT Hyderabad, India - 502285

Optical solitons in passively mode-locked fiber lasers provide a fundamental platform for exploring nonlinear wave dynamics governed by dispersion, Kerr nonlinearity, gain, and loss. Beyond conventional bright and dark solitons, hybrid multi-component states such as dark–bright (DB) and bright–dark (BD) soliton pairs have attracted considerable attention due to their vector nature and cross-phase modulation (XPM)-mediated coupling [1]. These states exhibit enhanced stability and enable new possibilities in nonlinear wave engineering. However, demonstrations using material-based saturable absorbers [2] remain limited by their fixed nonlinear response, restricting access to more complex soliton configurations. In parallel, soliton molecules formed by identical bright pulses have revealed rich internal dynamics, including sliding and oscillatory phase evolution [3].

In this work, we investigate dissipative soliton dynamics in a nonlinear polarization rotation (NPR)-based erbium-doped fiber laser, which serves as an artificial saturable absorber with continuous in-situ tunability. By systematically controlling intracavity polarization and pump power, we demonstrate the generation of a complete hierarchy of hybrid bright–dark soliton complexes within a single laser cavity. Starting from fundamental DB and BD soliton pairs, we experimentally realize all six possible three-component configurations, including bright–bright–dark (BBD), bright–dark–bright (BDB), bright–dark–dark (BDD), dark–bright–dark (DBD), dark–bright bright (DBB), and dark–dark–bright (DDB) states.

Furthermore, we extend the accessible soliton family to previously unreported higher-order configurations, including four-component dark–dark–bright–bright (DDBB) and dark–bright–dark–bright (DBDB) states, as well as a five-component bright–dark–bright–dark–bright (BDBDB) soliton complex. These states emerge from the interplay of XPM-induced inter-component coupling, birefringence-driven polarization evolution, and NPR-controlled nonlinear transmission. The observed structures exhibit stable mode-locking at a repetition rate of 8.015 MHz with high signal-to-noise ratios, confirming their nature as robust dissipative eigenstates.

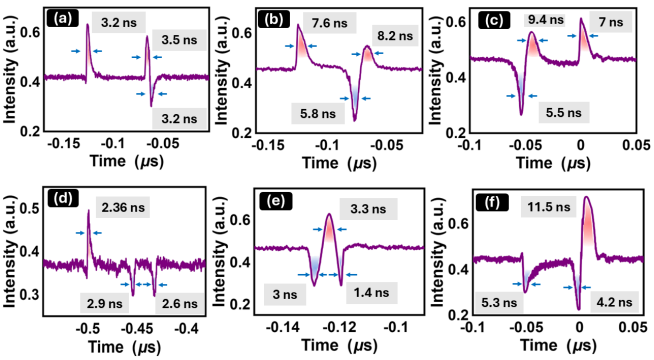

Figure 1: Single-pulse temporal profiles of all six three-component hybrid soliton states generated in the NPR-based EDFL.

Our results establish NPR-based fiber lasers as a highly reconfigurable platform for accessing the full parameter space of multi-component dissipative solitons. The demonstration of higher-order hybrid soliton complexes beyond previously reported limits significantly expands the experimental taxonomy of nonlinear localized waves and provides new opportunities for structured light generation, optical information encoding, and advanced photonic systems.

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Exploring the El Nino Climate Phenomena Using Eigenvalue Statistics and Network Theory

Nivedita Deo[1], Pooja Jain

[1]Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India

We integrate two methods (Network theory and Eigenvalue statistics) to investigate the complex El Nino/La Nina climate phenomena. We take the Tropical Pacific Ocean as the region under study and then construct threshold networks via correlation matrices of temperature time series and compute the highest node degree, total number of links, and the clustering coefficients for the networks. All these properties can be used as indicators and we notice that geographical locations near the equator and the tropics are the most important for the El Nino. In the eigenvalue statistics, we use the eigenvalue density distribution and find that the number of eigenvalues outside the random matrix bounds (outliers) increase in the El Nino years. The Shannon entropy and IPR are calculated to find out the most localized eigenmodes. This leads to the observation that the eigenvector components corresponding to the smallest and second smallest eigenvalue are most localized. We find that these eigenvalues can be used as indicators. Analyzing the components of the smallest and second smallest eigenvectors, we confirm the network result by identifying the equatorial and tropical locations which are most important thus addressing the complexity of the El Nino climate phenomena.

Dynamics of Kuramoto oscillators based on small systems

Samir Sahoo and Neelima Gupte

Department of Physics, IIT Madras, Chennai 600036.

We analyse the behaviour of Kuramoto oscillators based on small systems of two simplices. The simplices can share nodes, links and faces. Hysteretic behaviour and pattern formation can be seen for these systems, which can support pairwise, as well as higher order interactions. The evolution equations of the system can be reduced on the basis of symmetry considerations. Numerical studies of the reduced equations show phenomena like the Devil's staircase and Arnold tongue behaviour. This behaviour can in principle have relevance for realistic systems such as the brain connectome and nanomaterials.

To tip or not to tip – that is the question

Peter Ashwin

University of Exeter,United Kingdom

This talk will discuss attempts to understand practical aspects of the behaviour of non-autonomous systems (i.e. dynamical systems where the rules of evolution change with time). Although non-autonomous systems have been studied extensively, it remains hard to make statements about tipping behaviour in such systems without making some assumptions about asymptotic behaviour, for example that the system has autonomous past and future limits. Using the concept of pullback attractor, we note it is possible to understand changes associated with critical transitions/tipping points. We look at some consequences relating to predictability of ensembles in cases where the past limit attractor is chaotic, and for linked systems, where tipping may (or may not) propagate.

The Gross-Pitaevskii Bridge: Quantum Turbulence from Atomic Condensates to Cosmic Superfluids

A. Sivakumar[1], P. K. Mishra[2], and P. Muruganandam[1]

[1]Department of Physics, Bharathidasan University, Tiruchirappalli 620 024, Tamil Nadu, India
[2]Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

Quantum turbulence — the chaotic dynamics of quantized vortices in superfluids — manifests across an extraordinary range of scales, from micron-sized atomic condensates to kilometer-wide neutron-star interiors. Despite these vast differences, the Gross-Pitaevskii equation (GPE) provides a universal mean-field framework for describing vortex formation, turbulent cascades, and energy transport in compressible quantum fluids. In this talk, we synthesize results from five of our recent studies [1, 2, 3, 4, 5] demonstrating that the GPE establishes a direct bridge between laboratory Bose-Einstein condensates (BECs), self-gravitating dark matter condensates, and neutron-star superfluids through universal turbulence phenomenology.

In rotating atomic BECs, we showed that quantum turbulence exhibits two distinct spectral regimes: a Kolmogorov cascade with incompressible kinetic-energy spectrum $E(k) \sim k^{-5/3}$ at large scales and a Vinen-type k^{-1} scaling at smaller scales [1]. These cascades emerge from vortex clustering, nonlinear vortex interactions, and inverse energy transfer characteristic of two-dimensional quantum turbulence. Furthermore, simulations of merging rotating condensates revealed that collision-generated solitons decay into vortex tangles, producing transient strong turbulence and direct energy cascades [2]. Such condensate-merging dynamics provide experimentally accessible analogues for turbulent processes in astrophysical superfluids.

Extending the same framework to self-gravitating condensates modeling fuzzy dark matter halos, we demonstrated that colliding halos develop sustained Kolmogorov turbulence together with large-scale vortex expulsion mechanisms [3]. More recently, vortex-retention-mediated turbulent transitions were identified in bosonic and axionic condensates [5]. In these systems, gravity modifies the effective trapping potential and strongly influences vortex transport, angular momentum redistribution, and transitions between turbulent states. These results suggest that turbulence and vortex dynamics may leave observable signatures in galactic dark matter structures.

A particularly striking application arises in neutron-star interiors, where quantized vortices are believed to govern pulsar glitches. Using a microscopic GPE model of a spinning-down superfluid pinned to a crust potential, we discovered an anomalous energy-injection mechanism during turbulent vortex avalanches [4]. During spin-down, quantum pressure stores energy in compressible modes; when external forcing weakens, this energy is re-injected into the incompressible turbulent flow, thereby sustaining a Kolmogorov cascade precisely during angular momentum transfer to the crust. The turbulent state subsequently crosses over to a Vinen regime characterized by $E(k) \sim k^{-1}$, providing a possible microscopic explanation for observed glitch dynamics.

Taken together, these studies establish the Gross-Pitaevskii equation as a unifying theoretical framework for quantum turbulence across more than twenty orders of magnitude in physical scale. By connecting ultracold atomic condensates, self-gravitating dark matter halos, and neutron-star superfluids through common vortex and cascade dynamics, the results presented in this talk highlight the universality of superfluid turbulence and demonstrate how tabletop quantum-fluid experiments can illuminate complex astrophysical phenomena.

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On a matrix KdV6 equation

Pilar R. Gordoa[1], Andrew Pickering[1], Jonathan A. D. Wattis[2]

[1]Universidad Rey Juan Carlos, Madrid, Spain
[2]University of Nottingham, Nottingham, United Kingdom

The so-called KdV6 equation [1] has, since its discovery, been the subject of much interest. In this talk, we present a matrix generalization of the KdV6 equation [2] having a nonisospectral Lax pair. For this equation we construct a Bäcklund transformation and a nonlinear superposition formula that allows the iterative generation of solutions. As examples we give, for the direct matrix analogue of the scalar KdV6 equation, one and two soliton solutions for the case of 2×2 upper triangular matrices, and analyse their behaviour. In particular, in our study of these solutions, we have discovered that wave components can combine to produce rogue waves. In addition, we derive a related modified matrix equation, for which we construct ODE-type auto-BTs, in the sense that, although they provide mappings between solutions of PDEs, they mimic the auto-BTs for Painlevé equations (see [3] and [4] for examples of these type of auto-BTs for scalar and matrix partial differential equations, respectively.)

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Dynamics of neural network learning, covariance matrix ensembles and spectral statistics

Pragya Shukla[1],

[1] Department of Physics, Indian Institute of Technology, Kharagpur, India

A choice of appropriate weight matrices and their controlled variation is one of the most important tools to achieve desired learning outputs in an artificial neural network. Indeed, a conceptually and practically important route to investigate the dynamics of learning in increasingly complex modern neural networks is to represent the weight matrices by multiparametric random matrices. Deep neural networks often start as random weight matrix on the first layer but, with each subsequent layer transforming the input, training reshapes the kernel (covariance) matrix of the post activations at each layer with the eigenvectors of the latter representing learned features and the eigenvalues as the importance of those features.

A choice of the random weight matrix in the first layer gives rise to a covariance matrix of the post activations. The variation in the geometry of the data in feature space due to learning process manifest through the ensemble density dynamics in matrix space, with new correlations introduced among them, as well as in the ensemble parameters space. This is turn also results in spectral dynamics of the covariance matrix: as the data passes through layers, noise or irrelevant directions are suppressed, large eigenvalues corresponding to meaningful data patterns grow, new nonlinear combinations appear and the spectrum gradually becomes more structured. This spectral reorganization gradually converts random features into structured representations that capture the underlying structure of the data. An important measure for spectral analysis in this context is the density of eigenvalues of the covariance matrix; for example, a heavy-tailed distribution indicates that the representation contains features at many scales, with learning organizing the information hierarchically. This motivates us to theoretically analyze the spectral dynamics of a multiparametric covariance matrix ensemble with correlated elements. Our results lead to a single parameter governed formulation of the dynamics, with important implications which will be discussed in the talk.

Spatiotemporal Dynamics, Emergent Order, and Control in Reaction-Diffusion Systems

Pushpita Ghosh

School of Chemistry, IISER Thiruvananthapuram, Kerala 695551, India

In this talk, I will present our group's study on how externally applied electric fields influence pattern formation in ionic reaction–diffusion systems, focusing on the photosensitive chlorine dioxide–iodine–malonic acid (CDIMA) model. Using theory and simulations, we show that electric fields generate diverse spatiotemporal patterns, including Turing-like structures, traveling spots, and wave-splitting dynamics, governed by ionic charge properties. We also examine the interplay of electric fields with periodic photo-illumination, leading to complex superposed patterns with hexagonal and square symmetries. Further, periodic parametric perturbations drive rich spiral-wave dynamics, including breathing, drift, breakup, turbulence, and transitions to oscillatory clusters and uniform oscillations. Notably, we observe spiral regeneration with chirality reversal and multiphase cluster states arising from amplitude–phase interactions. These behaviors are organized into a two-dimensional phase diagram, revealing resonance-driven bifurcation cascades. Our results suggest new routes for controlled pattern manipulation in chemical systems.

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Experiment in progress, please enter quietly: Four Questions for Dynamical Young Experimentalists in India, with a few examples and illustrations

Rajarshi Roy

University of Maryland, College Park MD USA

When thinking about a career in science as one studies in colleges/universities and begins research in India, one is faced with some very basic questions. What are the experimental systems and tools of observation, and how do we analyze the information and make sense of what we observe? Though these questions may vary widely depending on circumstances, it may be possible to converge on a few basic themes. As the world changes and evolves, it is really important to spend a little time gathering information and thinking about how to make decisions that will lead to an interesting career for the next several decades.

Nothing is guaranteed, the uncertainties are huge, but some questions and guiding principles may help in beginning this experiment with one's life that will continue to guide us through a meaningful and interesting life journey. I will discuss what questions one may ask oneself and hope to learn from some of you what you think about such issues.

Numerical Investigation of Optical Parametric Amplification via Degenerate Four-Wave Mixing for Tunable Mid-Infrared Laser Generation at 2850 nm

R. Vasantha Jayakantha Raja[1]

[1]School of Electrical and Electronics Engineering, Center for Nonlinear Science and Engineering (CeNSE), SASTRA Deemed University, Thanjavur, India

This talk presents a theoretical framework for an optical parametric amplifier (OPA) driven by four-wave mixing (FWM) in a ZBLAN photonic crystal fiber (PCF) for generating mid-infrared pulses around 2850 nm. The presentation focuses on an OPA scheme based on degenerate FWM employing both picosecond-pulse and continuous-wave (CW) pump configurations.

The evolution of picosecond optical pulses during the FWM process is modeled using three coupled nonlinear Schrödinger equations (NLSEs), incorporating the effects of group velocity dispersion (GVD), self-phase modulation (SPM), and cross-phase modulation (XPM). Since analytical solutions are generally not feasible, a numerical approach is adopted throughout the study. For the picosecond-pulse pumping case, the coupled equations are solved using the split-step Fourier method combined with a fourth-order Runge–Kutta algorithm.

In this wavelength conversion scheme, the Stokes wavelength is accurately controlled through the degenerate FWM process by tuning the CW pump wavelength and the signal frequency of the picosecond pulses over a defined operating range. The coupled-amplitude model enables direct observation of coherent energy transfer among the three interacting waves along the fiber length, providing clear physical insight into parametric gain evolution, saturation behavior, and the influence of phase mismatch.

The results demonstrate that conventional fiber structures limit the idler generation amplitude within the spectral region of 2830–2870 nm, whereas the tapered fiber design enables continuous tunability and enhances idler amplification by approximately three orders of magnitude ($\sim$1000$\times$), significantly improving wavelength tunability and overall conversion performance.

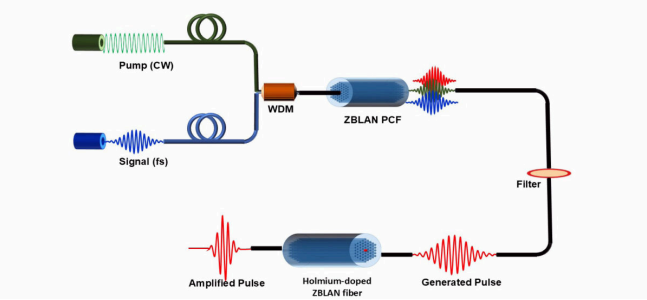

Figure 1: Schematic of the OPA system via FWM for tunable mid-IR generation.

Dynamical systems in arbitrary dimensions: A consistent generalisation of low-dimensional models

Ram Ramaswamy

Indian Institute of Science Education and Research, Berhampur, Odisha,India 760010

We have recently applied Clifford's geometric algebra to generalise the well-known Stuart Landau system to arbitrary dimensions $D > 2$. This approach recognises the special symmetries of the two-dimensional case and retains this feature in all dimensions, revealing a rich geometric and dynamical structure of the general model. We obtain exact solutions and describe the dynamical attractors and their basins of attraction in all dimensions. Since the model has D-dimensional rotational symmetry, we further study the dynamics of an ensemble of oscillators in higher dimensions with coupling chosen to either preserve or break this symmetry. The emergent collective states can have unusual dynamical behaviour such as partial synchronization (when only a subset of the variables coincide and oscillate) and partial oscillation death (when a subset of variables asymptote to different stationary values). Similar Clifford extensions of other limit cycle oscillator systems can be made, offering a consistent procedure for generalising dynamical systems to arbitrary dimensions.

Compact visible combs exploiting cascading of optical nonlinearities in dispersion-engineered waveguides

Ravi Pant[1]

[1]IISER Thiruvananthapuram

Frequency combs in the visible wavelength region have applications ranging from photon-level spectroscopy to optical atomic clocks and quantum communications. However, most of the visible combs are generated using bulky lasers that require high pump powers and cooling systems. In this work, we present cascading of optical nonlinearities in short-length tapers to achieve compact frequency combs in the visible wavelength region and demonstrate tuning of these combs over a wide wavelength range, demonstrating wideband phase matching.

Single- and multi-scale functional network analysis of heavy precipitation events during the Indian monsoon season: Lessons learned and best practices

Reik V. Donner[1,2], **Guruprem Bishnoi**[1,2]

[1]Magdeburg–Stendal University of Applied Sciences, Magdeburg, Germany
[2]Potsdam Institute for Climate Impact Research (PIK) – Member of the Leibniz Association, Potsdam, Germany

Strong rainfall events can have severe economic and societal impacts. Understanding the spatiotemporal dynamics underlying the emergence and propagation of such events requires robust statistical and dynamical analysis methods capable of capturing complex relationships within rainfall generating systems as well as with their controlling atmospheric processes.

During the past two decades, complex network approaches have been recognized as powerful tools for analyzing spatiotemporal patterns in climate data, offering new insights into extreme weather phenomena. Here, we systematically study the properties of functional climate network representations of strong rainfall events during the Indian summer monsoon season based on two conceptually related statistical association measures for event sequences, event synchronization strength and event coincidence rate, using events defined as daily precipitation sums exceeding a certain quantile of the local daily values of either all days or just of all days with precipitation. We demonstrate that certain climatologically meaningful links between strong rainfall events across distinct regions are only found in network representations based on event coincidence rates and rainy days only.

To gain further insights into the relevance of processes at different time scales, we additionally explore network representations obtained along with a discrete wavelet decomposition of daily precipitation sums. Consistent with previous single-scale analyses, our results indicate that Multi-Scale Event Coincidence Analysis (MSECA) mitigates previously unknown undesired effects of the previously developed Multi-Scale Event Synchronization (MSES) approach, which lead to a successive fragmentation of the network patterns obtained at longer timescales of several weeks. In general, we find distinct differences in the spatial properties of common network characteristics, further highlighting the sensitivity of functional network analyses of heavy precipitation to the choice of construction technique. These differences may adversely affect the identification of dominant heavy rainfall patterns and their underlying drivers, such as large-scale atmospheric circulation versus local thermodynamic mechanisms at daily to monthly temporal scales.

Our work underscores the importance of methodological rigor and the vast potential of complex network approaches in advancing the understanding of extreme rainfall events in monsoon-dominated regions. This comparison provides a foundation for developing standardized practices for functional network-based climate studies, enabling more robust assessments of extreme weather phenomena.

Unraveling the large-scale onset and withdrawal of Indian Monsoon through climatic phase transitions

R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600 036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600 036, India

The Indian monsoon (IM) plays a critical role in the economy of India. The Earth is surrounded by a narrow tropical belt known as the Intertropical Convergence Zone (ITCZ), which is characterized by deep convective clouds, heavy precipitation, and monsoon circulations. The annual migration of the ITCZ is the primary cause of the planetary-scale convectively connected system that results in IM. We use complex network analysis and community detection to create a novel classification of the tropical climate, which helps us understand the intricate spatiotemporal dynamics of the ITCZ and the teleconnection patterns that arises from it. We break down the complicated ITCZ dynamics into a simple but useful community structure that divides the tropics into seven areas having distinct dynamics. Even though IM is a planetary scale convectively coupled system, arising mainly from the seasonal migration of the ITCZ, the definitions of its onset and withdrawal are based on local weather observations, which are not very useful because they can pick up on fake onsets. With the help of climate networks, we show that small groups of locally defined onsets come together through two abrupt phase transitions defining large-scale onsets over the northeast and Indian peninsula. We also observe continuous growth of clusters in between these abrupt phase transitions. In contrast with the traditional notion that IM starts from Kerala and expands towards north and west, we propound that IM starts from northeast and expands towards west and north, eventually engulfing India in its entirety. Our analysis reveals that the onset of monsoon over the Indian peninsula critically depends on the characteristics of onset over the Northeast. In contrast with the current definitions, our network-based dates of onset results in a consistent and swift northward propagation of rainfall. Thus, using the new definition, we capture the onset of IM better than the existing conventional definitions.

Oscillating Cell Shapes: Patterns, Mechanisms, and Dynamics

Rumi De[1], **Arkayan Laha**[1], **Suman Halder**[1]

[1]Department of Physical Sciences, Indian Institute of Science Education and Research Kolkata, Mohanpur, Nadia 741246, West Bengal, India

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, residual strain states, and spatiotemporal chaos. Together, these formulations provide a unified theoretical framework for understanding the dynamics of the actomyosin cortex and the emergence of coordinated collective cellular motion during tissue development.

Parenclitic hypergraphs and their application in personalized cancer therapy

Stefano Boccaletti[1]

[1]CNR- Institute for Complex Systems, Italy

Understanding the differences between individual instances of the same complex system remains a central challenge, particularly in biological contexts. Parenclitic networks constitute a suitable means to detect deviations in correlations with respect to reference populations. I will introduce parenclitic hypergraphs, a general framework for identifying anomalies in higher-order correlations across arbitrary interaction orders. After validating the method on synthetic datasets and benchmark ones, I will show how it can be applied to patient-derived cancer organoids, capturing temporal changes in gene expression between healthy and cancerous tissues as the disease progresses. The approach not only reproduces known oncogenic signatures, but also reveals a previously unrecognized candidate therapeutic target. Since organoids are generated from individual patients, the method provides, for the first time, a viable protocol for personalized cancer therapy based on higher-order correlation patterns. These findings offer a novel, systems-level strategy for precision oncology grounded in complex systems theory.

ECG Parametrization in Three Acts

Sandip V. George[1]

[1]Department of Physics, University of Aberdeen, Aberdeen, United Kingdom

The electrocardiogram (ECG) is a widely used, cost-effective tool for assessing heart rate and rhythm. It records the heart's electrical activity as an almost repeating P–QRS–T waveform, whose shape and timing vary from beat to beat, resulting in a nonlinear and complex signal. Characterizing this variability is key to detecting and predicting cardiovascular disease. Here, we present three approaches from a nonlinear dynamical systems perspective using the PTB-XL database, which contains 21,837 10-second, 12-lead ECG recordings (100 Hz sampling) from 18,885 patients.

Nonlinear time series analysis: In our first approach we parameterize lead II ECG data and the relationship between leads II, aVL and V2 data using nonlinear time series techniques, including fractal dimensions, recurrence and information theory metrics. These metrics differ significantly between normal and pathological classes, as well as across the five PTB-XL superclasses. Incorporating these complexity measures as features also improves the performance of standard machine learning classifiers [1].

Dimensionality reduction: Our second approach uses a dynamic phase-normalization technique. By identifying successive R-peaks, we define a piecewise linear phase $\phi \in [0, 1)$ for each cardiac cycle, mapping each heartbeat, regardless of its duration (R–R interval), onto a standardized morphological vector. These "stretched" beats are then folded by averaging across cycles. The resulting waveforms are passed to a dimensionality reduction procedure, namely Locally Linear Embedding (LLE). Following [2], we embed the data first in three dimensions and subsequently in two. The embeddings lie close to a low-dimensional manifold (Figure 1), indicating that ECG variability is largely governed by a small number of underlying degrees of freedom.

ODE model-based approach: Our final approach employs delay-coupled oscillator models to represent cardiac electrical activity [3]. These models capture the interaction between physiological subsystems responsible for generating the ECG waveform and are capable of reproducing a range of normal and pathological rhythms. We infer model parameters directly from data using history matching, allowing us to identify regions of parameter space consistent with observed ECG signals. This provides a mechanistic interpretation of waveform variability, linking observed dynamics to underlying physiological processes. In particular, this approach enables us to explore how changes in parameters, such as coupling strength and delay between oscillators, lead to transitions between normal and pathological regimes, offering a complementary, model-based perspective to the data-driven analyses above.

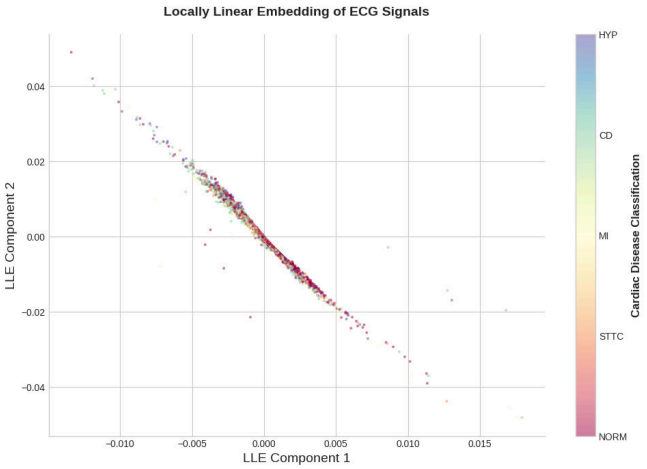

Figure 1: Low-dimensional representation of the ECG datasets from PTB-XL.

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Before the Collapse: Critical Slowing Down in Abrupt Desynchronization

Sarika Jalan

IIT Indore, India

transitions are common in complex systems, from power-grid failures to sudden loss of synchrony in neuronal and social networks. The Kuramoto modelhas long served as a paradigmatic framework for understanding collective synchronization in such systems. While continuous synchronization transitions are well understood and exhibit universal scaling behavior, a comparable framework for abrupt first-order transitions remains incomplete.

In this talk, we will show that abrupt desynchronization transitions in Networks Kuramoto oscillators exhibit clear signatures of critical slowing down. As the synchronized state approaches instability, both the relaxation time and correlation scale diverge, indicating emergent critical behavior even in a discontinuous transition.

Unlike previous studies of mixed-order transitions in spatially interacting systems, the observed divergences here arise without any underlying spatial locality, emerging purely through interactions in oscillator number space. We will further discuss how saddle-node bifurcation theory provides a natural dynamical explanation for these abrupt synchronization transitions, bridging nonlinear dynamics and phase-transition physics in complex networks.

Remote synchronization and multistability induced by slow drive in chaotic Chua's circuit

Tuhin Mahanty[1], Ayushi Saxena[1], Sangeeta Rani Ujjwal[1]

[1] Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

The response of Chua's circuit driven by a chaotic signal of variable time-scale is studied. When the driving signal is slower than the response and the driving strength is above a threshold, the Chua's circuit exhibits multiple stable attractors. The characteristic features of the attractors change as the driving strength ε increases; for instance, the attractors are double-scroll at low ε and are single-scroll when ε is high. To investigate the possibility of generalized synchronization (GS) between the drive and the response systems we employ the auxiliary system approach. When the time scales of the drive and response have a significant mismatch, different scenarios of *remote* synchronization (RS) between the response and auxiliary units are observed. In addition to complete synchrony between response and auxiliary systems indicating GS between drive and response, we notice that the response and auxiliary units can be lag synchronized and can also have correlated trajectories, indicating novel forms of RS. The slow drive can induce multistability between these RS states which disappears as the frequency of the drive increases and becomes comparable to the response of Chua's circuit.

Rogue wave solutions on the single- and double-periodic wave background of certain higher-order nonlinear Schrödinger family of equations

M. Senthilvelan[1]

[1]Department of Nonlinear Dynamics, Bharathidasan University, Tiruchirappalli – 620 024

In general, tsunamis and storms can be predicted hours or even days ahead of time. But in the oceanic rogue waves, prediction is not possible because rogue waves suddenly appear and disappear without any warning and trace. In nature, the surface of the ocean and the waves that occur on it show the single- or double-periodic patterns, and the theoretical studies on rogue waves on such background have received considerable attention in recent years. In this talk, I will discuss the construction of rogue wave solutions on the single- and double-periodic wave background for certain higher-order nonlinear evolutionary equations, namely Hirota equation, fourth-order nonlinear Schrödinger (NLS) equation and fifth-order NLS equation. In this process, first, we create the single- and double-periodic wave background with the help of Darboux transformation and nonlinearization of the Lax pair procedure. We then generate rogue waves over that single- and double-periodic wave background with the help of second linearly independent solution to the eigenvalue equation. Finally, we discuss the effect of higher-order dispersions on the amplitude and orientation of the background waves around the rogue waves.

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Manipulating phases in many-body interacting systems with subsystem resetting

Anish Acharya[1], Rupak Majumder[1], Shamik Gupta[1]

[1]Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India

Stabilizing thermodynamically unstable phases in many-body systems, such as suppressing pathological neuronal synchronization in Parkinson's disease or maintaining magnetic order across broad temperature ranges, remains a persistent challenge. In traditional approaches, such phases are stabilized through intervening in the dynamics of all system constituents or introducing additional interactions. Here, we offer a hitherto-unexplored alternative, namely, subsystem resetting, whereby intervention in the dynamics of only a part of the system, and that too only occasionally in time, is implemented through resetting its state to a reset configuration. Just playing with a few parameters, e.g., the nature of the reset configuration and the size of the reset subsystem, one achieves a remarkable and robust control over the phase diagram of the bare dynamics. We demonstrate that these universal effects span a wide variety of scenarios, including equilibrium and non-equilibrium, mean-field and non-mean-field dynamics, with and without quenched disorder. Despite the challenges posed by memory effects, we obtain explicit analytical predictions, validated by simulations [1].

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Layering imparts Stability: Hierarchical organization allows large complex systems to be robust

Aalhaad Bhatt[1], Mrinal Kanti Pal[1], and Sitabhra Sinha[1]

[1]The Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai 600113, India

The long-standing diversity-stability debate in ecology stems from a fundamental paradox: while empirical observations suggest that densely connected, highly diverse ecosystems, such as tropical rainforests and coral reefs, exhibit stability, mathematical models — stemming from May's original approach based on linear stability analysis around arbitrary equilibria to global dynamics of coupled generalized Lotka–Volterra systems — suggest that increasing diversity or connectivity should lead to higher probability of instability. Resolving this contradiction is crucial especially in the face of accelerating biodiversity loss, necessitating theoretical frameworks that reconcile these opposing perspectives and generate ecologically realistic predictions.

Most earlier theoretical studies have used pre-assembled networks of species, thereby missing out the crucial role played by the evolving, dynamic nature of species assembly (through invasions and extinctions) in real ecosystems. By incorporating sequential species introduction in our model presented here, we demonstrate that higher diversity can coexist with robustness of the complex system to perturbations — in contrast to earlier modeling approaches. In contrast to most models that assume species homogeneity and intrinsic stability for all species, we explicitly distinguish between producers and consumers, with the latter not possessing inherent stability. We find that reducing consumer proportion relative to producers enhances overall diversity. Further, consumer species extinctions trigger much larger cascading events than producer extinctions. Another critical aspect we uncover is the variety of interaction types among species which have received relatively limited theoretical attention. We show that incorporating more exploitative interactions leads to higher stability, with a greater proportion of predation among the consumers enhancing system robustness and supporting greater species diversity.

Most importantly, we address a relatively unexplored phenomenon in community assembly, viz., how trophic levels emerge from sequential species additions and deletions. Our findings reveal that ecosystems with more trophic levels exhibit greater robustness to perturbations, emphasizing the stabilizing role of hierarchical organization in complex networks.

Proteins as Complex Systems

Somdatta Sinha

Indian Institute of Science Education and Research (IISER) Kolkata, Mohanpur, West Bengal,India 741246

Proteins are important macromolecules in the cell involved in cellular structures and regulating metabolic processes. The primary structure of a protein is made up of a linear chain of amino-acids synthesized through transcription and translation of the corresponding gene/DNA sequence inside the cell. The functional protein is a three-dimensional (3D) structure that is formed due to spontaneous or assisted folding of the linear chain decided by the physicochemical forces exerted by the size, charge and chemical nature of the amino acids. The 3D structure essentially determines the function known as the "Structure-Function Paradigm" of the protein in structural biology. Predicting the 3D structure of proteins is essential to the understanding of structural variations, functions, and protein design/engineering. Traditionally, large scale force-field calculations using Molecular Dynamics are used to study the evolution of the 3D structure under the influence of the different chemical interaction potentials. In recent years machine learning approaches are used. From a nonlinear dynamics and complex systems view, we propose that the functional protein structure can be visualized as a complex system, where hundreds and thousands of atoms of the amino acids ("parts") have millions of nonlinear interactions, leading to the cooperative and collective behaviour ("emergent function") such as, self-organization, binding of other molecules, catalysis, and allostery. We then model the 3D structure of proteins using complex networks, where the amino acids are the nodes, and links are the physicochemical forces that hold any two amino acids together. This approach can clearly separate the known structural classes of proteins (e.g., the sheets and helices) through analysis of the network parameters. It can also explain the large functional differences observed in proteins and their mutants that have insignificant structural variations which is not easily identifiable using standard structural biology methods, and thereby questioning the universality of the "Structure-Function Paradigm".

Mechanics promotes synchronization in excitable tissue

Soling Zimik[1], Sitabhra Sinha[2]

[1]Indian Institute of Science Education and Research Thiruvananthapuram, Thiruvananthapuram, India
[2] The Institute of Mathematical Sciences, Chennai, India

Electrical activity drives muscle contractions in many vital organs that perform essential body functions, including the beating of the heart and the contractions of smooth muscle in the uterus and gastrointestinal tract. Cells in these organs can elicit electrical excitations, known as action potentials, which are characterized by sharp elevations of transmembrane electric potential of the cells. Although the process by which electrical excitation triggers contraction is well studied, less is known about how cells coordinate their activity across tissue, especially in these organs that are made up of different cell types with distinct activity patterns. Understanding this collective behavior is important because tissue-scale synchrony underlies functions such as the heart's pumping action, and its failure can contribute to disorders like arrhythmia, irritable bowel syndrome, and preterm labor. Mechanical interaction among cells in the tissue, because of their long-range nature, serves as a mechanism by which the system can achieve coherent electrical activity across tissue [1].

Cells that respond to electrical stimulation can be broadly classified into two categories: non-oscillatory excitable cells, which generate action potentials only when driven beyond a threshold by an external stimulus, and oscillatory cells, which exhibit intrinsic periodic activity. A heterogeneous excitable tissue consists of a mixture of these two cell types, and the resulting spatiotemporal patterns of electrical activity depends on their relative proportions as well as the strength of intercellular coupling. Such systems can exhibit a range of excitation patterns, including clustered oscillations, travelling waves, and coherent activation (see Figs. (a)–(d)). Beyond local diffusive interactions, the inclusion of mechanical coupling between cells promotes the emergence of coherent electrical activity (compare Figs. (e) and (f)), which in turn leads to synchronized muscle contraction, a crucial requirement for the proper functioning of excitable organs.

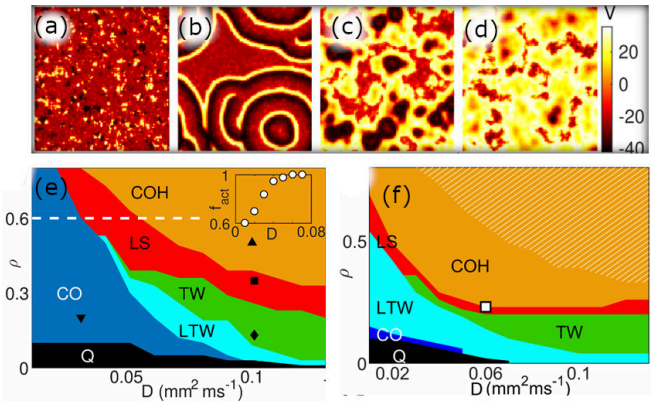

Figure 1: Electrical excitation patterns and phase diagram: Top-row figures show the excitation patterns, namely, (a) clustered oscillation **CO**, (b) travelling waves **TW**, (c) local synchronization **LS**, and (d) coherence **COH**, that emerge in a heterogeneous excitable tissue comprising oscillators and non-oscillators as the diffusive coupling strength between the cells increases from (a) to (d). The colorbar represents the electric potential of the tissue in millivolts. Bottom-row figures show the regions where the various excitation patterns occur in the space spanned by oscillator density ρ and diffusion constant D in the absence (e) and presence (f) of mechanical coupling. The expansion of the coherent region in fig. (e) as compared to (f) demonstrates that mechanical interaction promotes synchronized electrical activity in the system.

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Tipping in forced and coupled ecological systems

Syamal K. Dana[1,2]

[1]Centre for Mathematical Biology and Ecology, Department of Mathematics, Jadavpur University, Kolkata 700032, India
[2]Division of Dynamics, Lodz University of Technology, 90-924 Lodz, Poland

I will share our experience on tipping phenomenon in forced and coupled ecological systems. We observed partial tipping in periodically forced 2D and 2D systems where the system does not tip from any random initial conditions rather depends upon an ensemble of initial conditions of the basin of attraction of the systems.

In addition, the tipping probability shows a resonance-like frequency response against external forcing considered as an analogue of seasonal variation of the environment. In coupled systems, we find an interesting phenomenon of indirect tipping, when a driving system may not tip, while the driven system may tip to an alternate state[1, 2, 3].

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Quantum Chaos Across Scales: From Single Particles to Many-Body Systems

Soumik Bandyopadhyay

Indian Institute of Science Education and Research (IISER) Thiruvananthapuram, Kerala, India

Understanding the emergence of quantum chaos from the single-particle level to fully developed many-body dynamics is a central challenge in modern physics, with implications for ergodicity, thermalization, and quantum information. In recent years, the Sachdev–Ye–Kitaev (SYK) model has played a pivotal role owing to its ability to capture strongly correlated regimes, maximal quantum chaos, and its deep connections to quantum gravity.

In this talk, we shall discuss how variants of the SYK model can be used as a versatile platform to systematically explore the onset of chaos in quantum systems. We begin by analyzing a Yukawa variant of the SYK model, where we identify clear dynamical and spectral signatures marking the crossover from single-particle to many-body quantum chaos. Furthermore, we show that a variable-range quadratic SYK model, in which the interaction range can be tuned, enables controlled access to ergodicity transitions in the many-body spectrum. Using spectral diagnostics, we map out regimes spanning localized, non-ergodic extended, and fully chaotic phases.

Finally, we briefly highlight how the onset of many-body chaos naturally leads to transitions in quantum complexity. By analyzing measures such as nonstabilizerness, entanglement, and fractal properties of quantum states, we demonstrate that complexity transitions arise as a direct consequence of the underlying chaotic dynamics, revealing a unified picture connecting spectral chaos with the structure of quantum states in Hilbert space.

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Impact of Asynchronicity on Complex Systems

Sudeshna Sinha

Indian Institute of Science Education and Research Mohali, Sector 81, SAS Nagar, PO 140306, Punjab, India

Asynchronicity is a fundamental characteristic of complex systems, in the presence of natural heterogeneity in the constituent units, and in the absence of external forcing or a common drive that may act as a global clock regulating the extended system. However, the impact of asynchronicity on spatiotemporal patterns is still not commonly explored. Here we will demonstrate how networks of chaotic systems can be tamed by asynchronicity in dynamical evolution. We will provide numerical evidence as well as analytical results to support this, in a range of systems.

We will first recall early results on the dynamics of logistic maps coupled diffusively [1, 2], as well as through threshold-activated coupling [3], and demonstrate the emergence of stable spatiotemporal steady states under increasingly asynchronous evolution. We then go on to explore the impact of asynchronicity on a system of coupled chaotic model neurons [4, 5]. Our key finding is that asynchronicity can suppress neuronal oscillations under sufficiently strong coupling. 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. 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 effects of asynchronicity. We also analyze the dynamics of large systems, in a time-averaged framework. Our analysis yields values of critical coupling very close to that obtained from simulations.

We then propose a model of asynchronicity that enables us to explore the impact of temporal asynchronicity, in the presence of spatial correlations. Our central finding here is that asynchronicity strongly suppresses neural activity, while spatial correlations mitigate the effects of asynchronicity aiding neuronal activity. When a system evolves through asynchronous updates of random sites, one obtains complete activity quench over a large range of coupling strengths. In contrast, when clusters update stochastically i.e. when spatial correlations are present in the set of updating sites, neuronal activity persists. Thus there exists a stark difference in the dynamics of systems with randomly updated sites and randomly updated clusters, *even when the number of synchronously evolving sites is exactly the same*. We also analyze the dynamics of effective reduced-order models mimicking the full dynamics, to provide understanding of this intriguing phenomena. Stability analysis of these models captures the qualitative trend of chaos suppression for very small cluster sizes, as well as the rapid loss of chaos suppression with growing cluster size. So these results demonstrate that spatial correlations can strongly temper the effect of asynchronous evolution.

In summary, broadly speaking, this set of results indicate that the inherent randonmess in asynchronous updates has profound implications for the collective dynamics of large interactive systems. Further, counterintuitively, the temporal disorder induced by asynchronicty, yields order in the dynamics of coupled chaotic systems.

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Evolution of cooperation in networks with environmental feedback

Supratim Sengupta[1], Maria Kleshnina[2], Amit Basak[1]

[1]Department of Physical Sciences, IISER Kolkata, Mohanpur, India
[2]Queensland University of Technology, Brisbane, Australia

Individual actions can modify the environment and consequently the costs and benefits associated with strategic interactions within a social network. Recent work has shown that transitions between different environmental states, characterized by games with distinct payoff structures, can make it easier for cooperators to spread in structured populations. However, knowledge of the environmental state often modulates individual strategies and consequently shape collective outcomes. We critically assess whether such knowledge can affect collective welfare by comparing scenarios in which player's actions depend on their knowledge of the environmental state with those in which their actions are independent of the state. Using both theoretical analysis and numerical simulations, we obtain the conditions under which cooperation evolves in either scenario across all deterministic rules governing transitions between environmental states. Surprisingly, we find that environmental knowledge can sometimes be detrimental to cooperation, thereby pointing to the existence of a "knowledge curse". Nonetheless, for a substantial class of game–transition rules, such knowledge remains beneficial. Our results show that conditioning behavior on the environmental state does not universally promote cooperation and may, in some cases, make it more difficult for cooperation to evolve in social conflicts.

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Nonlinear Waves in Multicomponent Long Wave - Short Wave Resonant Interaction System

T. Kanna[1]

[1] Nonlinear Waves Research Lab, PG and Research Department of Physics, Bishop Heber College, Affiliated to Bharathidasan University, Tiruchirapalli 620 017, India

Long wave–short wave resonance is a nonlinear wave interaction process that occurs when the phase velocity of a long wave (LW) approximately or exactly matches the group velocity of a short wave (SW). Recently, significant attention has been given to such interactions involving multiple short waves resonantly coupled with a long wave.

In this talk, we focus on a new (1+1)-dimensional multicomponent Yajima–Oikawa system consisting of two short waves and one long wave, incorporating general nonlinear coupling. This system is derived from a physically relevant set of three coupled nonlinear Schrödinger equations using the multiple scale perturbation approach. The resulting model generalizes the existing LSRI system and is established under suitable assumptions with a solid physical foundation in nonlinear optics and fluid mechanics.

Using Hirota's bilinear method, we construct bright N-soliton solutions for arbitrary N, expressed in Gram determinant form. The existence of general three-soliton solutions suggests the integrability of the system. These multi-soliton solutions enable a detailed study of soliton interactions. In particular, the two-soliton solution reveals intriguing collision dynamics, including two distinct types of shape-changing collisions characterized by energy redistribution and amplitude-dependent phase shifts.

We further investigate the influence of system parameters on soliton interactions. Finally, under velocity resonance conditions, we demonstrate the formation of soliton molecules and analyze their dynamics. The roles of coupling coefficients and four-wave mixing effects are also examined.

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Synchronous and desynchronous states of coupled oscillators

Tomasz Kapitaniak

Lodz University of Technology, Poland

Understanding the collective behavior of dynamical systems is essential for explaining various emergent phenomena in natural and engineered settings. A key step in this process is formulating an appropriate mathematical description of the individual systems and network of systems. In this context, a range of physical systems is considered here, including the classical pendula, superconducting Josephson junctions, power grids, and various others. Despite the diversity of the systems in terms of physical structure and their application domains, they exhibit strikingly similar dynamical features, namely, phase dynamics governed by inertia and damping and in their response to external forcing. This observation creates interest and motivates a search for a unified theoretical framework capable of capturing the fundamentals of their dynamical behaviors exhibited across the systems. This talk critically examines the up-to-date research activities on the dynamics of the second-order phase oscillator, henceforth claimed here as a universality class by its own merit as a simple nonlinear dynamical model representing a broad class of physical systems. It offers a common mathematical framework to develop a comprehensive understanding, from a general perspective, that bridges, the theoretical and experimental observations of pendulum motion, Josephson junctions, and power grids and their collective behaviors. While each of these systems has been discussed in disparate physical contexts, their underlying mathematical structures reveal strong commonalities. In particular, we highlight the importance of analyzing these systems through the lens of nonlinear phase dynamics to uncover their shared mechanisms and system-specific variety of behaviors as well. This survey mainly focuses on some specific interrelated themes: (i) collective phenomena and emergent synchronization; (ii) the role of heterogeneity in terms of system parameters and the effect of noise on the emergent dynamics; (iii) multistability and complex transient regimes; (iv) the integration of machine learning for model discovery, control, and prediction; and (v) the broader applicability of phase oscillator models across diverse domains beyond the canonical systems considered here. By systematically comparing the dynamical behaviors of the varied physical systems within a cohesive mathematical framework of second-order phase oscillators, this review seeks for the universal and distinctive features of nonlinear dynamics of the three systems, their collective behaviors such as emergent synchrony, partial synchrony, or chimera states, and specifically explains real-life phenomena, and crowd synchrony that may lead to a collapse of a footbridge and the failure of a power grid. Besides our main emphasis on these system, brief notes have been added on other systems where this second-order phase model explains their dynamical properties. A broad synthesis on the topic will not only deepen our theoretical understanding but also suggest any design and control of complex dynamical systems in both natural and engineered settings.

Projective Synchronization in Chaotic Circuits

Thounaojam Umeshkanta Singh

Department of Physics, School of Engineering and Applied Sciences,
Bennett University, Greater Noida, Uttar Pradesh 201310, India

Projective synchronization refers to a regime in which a response system tracks a chaotic drive up to a constant amplitude scaling factor [1]. In this work, we experimentally demonstrate the robustness of projective synchronization using coupled nonlinear electronic circuits. Specifically, we report the hardware realization of projective synchronization in Sprott-based chaotic oscillators [2]. The analog implementation reliably produces amplitude-scaled replicas of the drive attractor in the response system, confirming that the geometric structure of the chaos is preserved under coupling. Importantly, unavoidable component tolerances in resistors and capacitors lead to spontaneous transitions between in-phase and anti-phase projective synchronization, revealing multiple coexisting synchronized states accessible in physical systems. These results establish a simple and versatile circuit platform for exploring scalable forms of chaos synchronization, with potential relevance to secure communication architectures, signal encoding, and nonlinear information processing.

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The constructive role of transient chaos in complex systems

Ulrike Feudel

ICBM, Carl von Ossietzky University, Oldenburg, Germany

Permanent and transient chaotic dynamics has been found in many applications like mechanical oscillators, laser physics, neuroscience, ecology and coupled systems of different kind to name only a few. Recently, the focus has shifted to transient chaos on chaotic saddles as a phenomenon which provides new opportunities for complex dynamics. We show how chaotic saddles as unstable sets can lead to extraordinary long chaotic transients or even permanent chaos in coupled oscillatory systems or in non-autonomous dynamical systems [1].

On the one hand, long chaotic transients have been manifested in an increasing interest in a phenomenon called metastability [2], in which a system switches between different metastable dynamical states. We show, how chaotic saddles comprising different spatial-temporal patterns can arise in coupled neuronal systems, capable of pattern switching similar to processes appearing in the brain [3]. On the other hand, transient chaos can become extraordinary long-lived or even permanent when systems exhibiting transient chaos in their dynamics are coupled. For this second possibility we discuss the constructive role of transient chaos in networked ecosystems, so-called metacommunities, where transient chaotic oscillations give rise to a complete desynchronization of originally synchronized population patches [4] and in coupled ecological systems, where transient chaos prevents the extinction of species [5].

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Quantum Simulation: Atomtronics & Interferometry

Utpal Roy

Department of Physics, Indian Institute of Technology Patna, Bihta-801106, India

Ultracold atomic gases provide a versatile platform for investigating coherent nonlinear quantum phenomena and developing emerging quantum technologies. In this talk, I will focus on Bose–Einstein condensates confined in engineered trapping geometries, including harmonic, optical lattice, and ring-shaped potentials. These systems support a rich variety of nonlinear excitations, such as solitons and quantum droplets, as well as coherent matter-wave dynamics in complex potential landscapes. In particular, Bose– Einstein condensates confined in optical lattices offer promising opportunities for quantum simulation. I will further discuss applications in atomtronics and matter-wave interferometry, highlighting the implementation of a matter-wave tiltmeter and a Sagnac interferometer.

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

Vaibhav Madhok

Indian Institute of Technology Madras, Chennai,India 600036

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.

The Complex Dynamics of Monsoonal Storm Systems and Their Role in Extreme Rainfall Events

Vishnu S. Nair

School of Earth, Environmental and Sustainability Sciences, Indian Institute of Science Education and Research, Thiruvananthapuram, India

Monsoon low-pressure systems (LPSs), relatively weak tropical disturbances, are a major source of extreme rainfall during the Indian summer monsoon. This study examines the nonlinear link between LPS dynamics and extreme precipitation, and how LPS rainfall modulates interannual variability of Indian Summer Monsoon Rainfall (ISMR). We find a strong association between LPS-induced rainfall and ISMR: excess-ISMR years feature more frequent and/or intense LPS-related extremes, whereas drought years show much weaker LPS rainfall. Excess years also have higher ambient humidity and stronger LPS-driven ascent. However, standard dynamical intensity metrics for LPSs change little, indicating a mismatch between rainfall intensity and conventional measures of LPS strength. We analyze how LPS rainfall extremes scale with thermodynamic and dynamical factors, following O'Gorman and Schneider (2009)[1]:

$$P_e \sim -\left\{ \omega_e \left. \frac{dq_s}{dp} \right|_{\theta^*, T_e} \right\}, \qquad (1)$$

where P_e is an extreme precipitation rate, ω_e the associated upward vertical pressure velocity, and $\{\cdot\}$ a mass-weighted tropospheric integral. The pressure derivative of saturation specific humidity dq_s/dp is evaluated along a moist adiabat of constant saturation equivalent potential temperature θ^* at the conditional mean temperature T_e.

In a regime where increased moisture raises precipitation without large changes in rotational intensity or ascent magnitude, purely thermodynamic effects are non-negligible but explain only about 10% of rainfall variability (See Figure 1). Changes in vertical ascent dominate the control on extremes. Stronger ascent in the southwestern quadrant of the LPS is likely tied to anomalous meridional moisture gradients, underscoring the central role of vertical motion. This dominance of ascent aligns with super–Clausius–Clapeyron scaling of extreme rainfall. Although such enhanced rainfall, combined with moist vortex instability[2], could intensify LPS circulation, we do not find robust evidence of intensification in conventional LPS metrics.

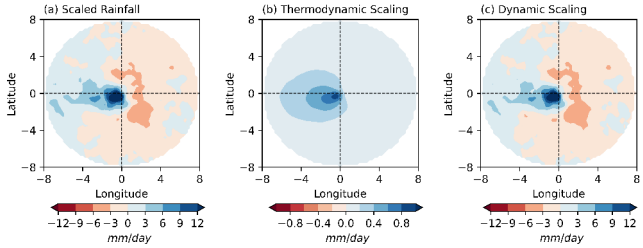

Figure 1: Changes in rainfall between excess and drought years estimated using (a) both dynamic and thermodynamic components, (b) only thermodynamic components, and (c) only dynamic components.

We further find that stronger horizontal pressure gradients and higher near-center wind speeds produce more compact, intense LPSs in excess-ISMR years, clarifying the link between LPS dynamics and extreme rainfall. While conventional metrics do not conclusively show vortex intensification, some strengthening may go undetected.

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Emergence and Control of Quantum Synchronization in Nonlinear Oscillators

B. Vigneshwar[1], D. V. Senthilkumar [2] and V. K. Chandrasekar[1,*]

[1]Department of Physics, National Institute of Technology, Tiruchirappalli–620015, Tamil Nadu, India
[2]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram-695551, Kerala, India
[1,*]Centre for Nonlinear Science & Engineering, School of Electrical & Electronics Engineering, SASTRA Deemed University, Thanjavur–613401, Tamil Nadu, India

[*]Presenting author: V. K. Chandrasekar

Synchronization is a central route to collective order in nonlinear systems, where interacting units adjust their rhythms through phase locking and frequency entrainment. While this classical picture is well captured by Arnold tongue structures, synchronization in the quantum regime is qualitatively reshaped by coherence, fluctuations, dissipation, and spectral hybridization. Here, we discuss how these ingredients modify synchronization in coupled self-sustained quantum oscillators and reveal mechanisms with no direct classical counterpart.

Using phase-state probability distributions and two-time correlation spectra, we show that coherent exchange coupling leads to dressed-state-mediated synchronization. In contrast to classical entrainment, where frequency locking is associated with the collapse of distinct spectral peaks into a single common frequency, the quantum system retains a resolved spectral doublet arising from hybridized dressed states. This dressed-state structure enhances phase locking and enlarges the synchronization region beyond the classical Arnold tongue.

We further show that anisotropic counter-rotating interactions provide an independent control mechanism for quantum synchronization. By breaking the continuous rotational symmetry of the quantum limit cycle, anisotropy induces symmetry-breaking bifurcations and oscillation-death-like steady states in phase space. At the same time, it suppresses bistable phase locking by eroding dressed-state hybridization. In detuned oscillators, the competition between anisotropy and frequency mismatch produces mode-dependent localization and intermediate dynamical regimes absent in the identical case. These results establish quantum synchronization as a spectral and symmetry-controlled collective phenomenon, rather than a simple quantum extension of classical entrainment.

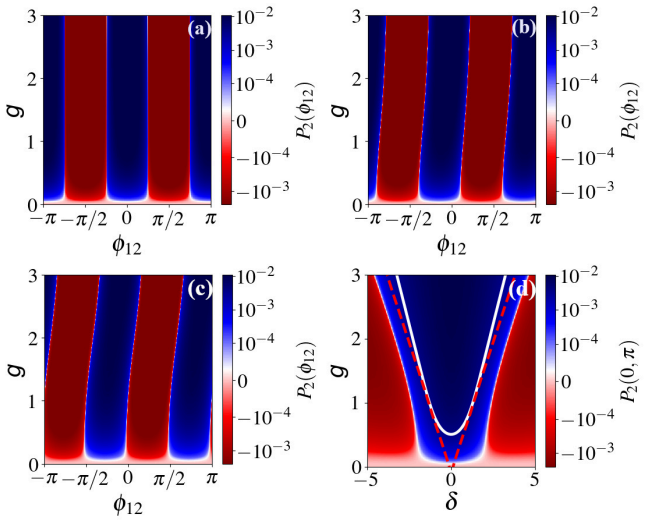

Figure 1: Quantum phase synchronization in coupled self-sustained oscillators. Panels (a)-(c) show the relative phase distribution $P_2(\phi_{12})$ for different detunings, revealing phase locking near 0 and π. Panel (d) shows the corresponding synchronization region in the (δ, g) plane, where the quantum phase-state measure extends beyond the classical Arnold tongue.

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Contributory Talks

CNSD 2026

Dynamics of binary stars using Recurrence Quantification Analysis

Anisha Kashyap[1], Devraj Pawar[2], Ranjeev Misra[1], G. Ambika[3] and Sandip George[4]

[1]Inter-University Centre for Astronomy & Astrophysics, Pune-411007, India
[2]R. J. College, Ghatkopar (W), Mumbai-400086, India
[3]IISER, Thiruvananthapuram-695551, India
[4]University of Aberdeen, King's College, Aberdeen, AB24 3FX, United Kingdom

Studies of astrophysical objects mostly rely on their observational data, which is a real challenge requiring physical analysis with large costs. Recently, because of the enhanced sensitivity of modern observatories, very large sets of data are available for analysis and classification. Conventional classification frameworks for eclipsing binaries employ curve fitting and dimensionality reduction techniques to characterize system morphologies. Nevertheless, these methods do not account for the inherent dynamic variability in close binary systems caused by tidal interactions, starspots, and energy and mass transfer.

In this work, we proposed an alternative method to classify one such set of objects, binary stars, by analyzing observational data from the Kepler mission. For this, we recreate the dynamics underlying the data using delay embedding and compute measures from the pattern of recurrences in the dynamics [1,2]. We compute measures like Recurrence Rate (RR), Determinism (DET), Laminarity (LAM), Entropy (ENT) from the data of the binary stars of different classes, semi-detached, overcontact and ellipsoidal ones. These recurrence-based measures capture nonlinear dynamical features that are often overlooked by traditional techniques [3], enabling the differentiation of systems with similar folded light curves but distinct dynamical behaviors. Furthermore, the approach is computationally efficient, requiring only a short segment ($\sim$3000 points) of the light curve.

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SPR based Symmetric Lattice Photonic Crystal Fiber infiltrated with Magnetic fluid for magnetic field detection

Aparna A Nair[1], M.S.Mani Rajan[1]

[1]Anna University, University College of Engineering, Ramanathapuram 623513

The measurement of magnetic fields is essential for industrial and navigation applications in defense [1]. In sensor industry, magnetic field sensor emerged as a imperative sensor. By incorporating surface plasmon resonance (SPR) with photonic crystal fiber, sensing characteristics like the sensitivity, detection range and figure of merit (FOM) can be improved [2]. In this work, we proposed a PCF with octogonal ring structure for magnetic field detection. The PCF is designed with pitch value of 4 µm and largest air hole size (d4) is 6 µm. The diameter values of other airholes are adopted as d3 = d4/2, d2 = d4/4 and d1 = d4/8 for better modal confinement and enhanced light-matter interaction. In order to use the proposed design for magnetic field sensing, two air holes with diameter (D) is selected near the core for infiltration of magnetic fluid (MF) and these airholes are coated with gold material of 40 nm for exciting plasmons through the phenomena of surface plasmon resonance. To improve the sensing performace, SPR will help through the coupling between the core guided mode and plasmonic mode.

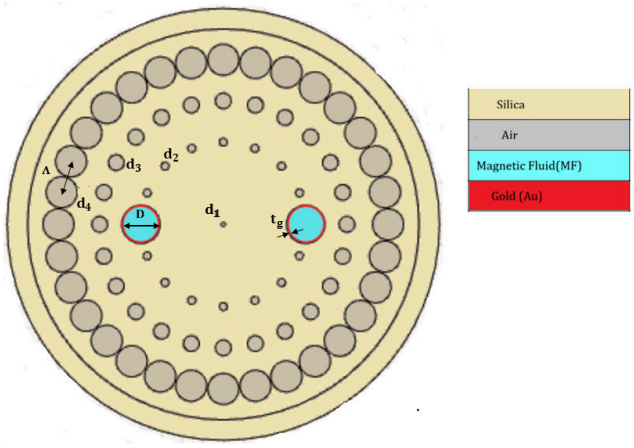

Figure 1: The Proposed Octagonal PCF infiltrated with magnetic fluid.

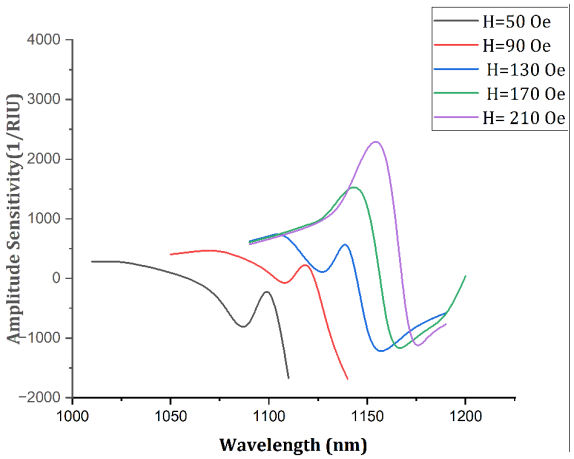

Figure 2: Influence of different magnetic field on Amplitude Sensitivity.

The performance of proposed PCF sensor can be analyzed further using the amplitude interrogation method using the expression given below

$$S_A(\lambda, n_a) = -\frac{1}{\alpha(\lambda, n_a)} \frac{\partial \alpha(\lambda, n_a)}{\partial n_a} \tag{1}$$

Where α shows the confinement loss as function of wavelength and refractive index in dB ,$\partial\alpha(\lambda, n_a)$ is the difference of confinement loss between two consecutive refractive index (n_a).

In this study we have designed and studied highly sensitive PCF-SPR sensor infiltrated with magnetic fluid. The optimized structure achieved a maximum amplitude sensitivity of 1321.9 (1/RIU) in the refractive index range of 1.43316-143964.

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Predicting climate change effects: from ocean carbon sinks to population dynamics of living systems

Balakrishnan Ashok[1]

[1]Complex Systems & Soft Matter Physics Lab, Centre for Applied Sciences, International Institute of Information Technology Bangalore (IIIT-B), 26/C, Electronics City Phase-1, Hosur Road, Bengaluru 560100, INDIA.

We show how changing temperature & climate profoundly influence the dynamical evolution of ecosystems and population dynamics.
Our conceptual nonlinear model [1] for the oceans predicts the spatiotemporal evolution of CO_2 of each ocean, and how the major freshwater flow of the Amazon river has significant effects on CO_2 sequestration trends and act as a critical controller of climate.

We show how changes in the North Atlantic get reflected in startling changes in the Indian Ocean, indicating a close coupled behaviour between the two, also reflected in our computation of the basins of attraction. We also predict, on the basis of stability analysis of the system equations, salinity oscillations between the Southern and South Atlantic Oceans, such as are seen in the South Atlantic Antarctic Intermediate Water (AAIW) reported in the literature.

The Indian Ocean salinity fixed point is seen to be at a bifurcation point. Our work predicts the location of carbon sinks in the oceans and how much CO_2 would be absorbed by each ocean with increasing time, which would influence atmospheric temperature. Our predictions are in broad agreement with previously reported observations in the literature.

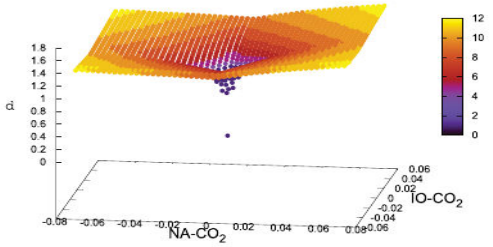

Figure 1: Symmetric basin of attraction, N. Atlantic & Indian Ocean CO_2 – indicative of coupling between the two oceans.

How such changes in temperature and other perturbative influences in the environment affect population dynamics is addressed in our work [2]. We predict the dynamical evolution of insect populations, with ambient temperature, body mass and density-independent mortality rates influencing the trajectory of the system. We show that temperature acts as a crucial control parameter determining the extent of population and biomass of a colony. Perturbations to the population completely change the system dynamics and the evolution of the colony, to show rich dynamic behaviour such as period-doubling, intermittent chaos, period-halving and chaotic bubbles.

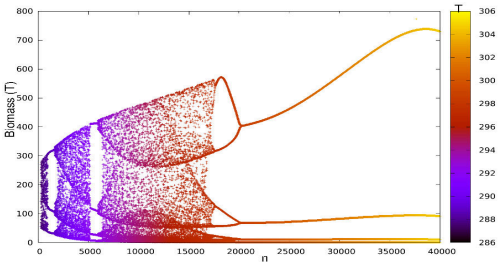

Figure 2: Biomass plotted over various generations n, showing a dependence on temperature T.

Effects of environmental changes also affect other phenomena in living systems such as transpiration effects & the rise of sap in plant xylem [3]. The comparative extent of capillary & hydrostatic forces, as well as ambient temperature controls the dynamics of the flow of sap, and the nature of the stability.

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Propagation of ultra-short pulses in resonant optical fiber with stimulated Raman Scattering Effect

B. Poojalini [1], B. Kalithasan[1]

[1]PSNA College of Engineering and Technology, Dindigul,India

In nonlinear optical fiber communications, soliton propagation occurs. By studying the continuous-wave steady-state solution along the fiber, introducing a tiny perturbation and then analyzed modulational instability (MI) . This is crucial for generating ultrashort pulses and is essential for high-speed optical communication systems. In this work, a steady light beam propagating in an optical fiber doped with a two-level atomic resonant medium is investigated including the effects of stimulated Raman scattering (SRS). The system is modeled using the governed Nonlinear Schrodinger–Maxwell Bloch (NLSE–MB) equations and These equations include Kerr nonlinearity, group-velocity dispersion (GVD), Raman effects, and atomic resonance inside the fiber. These equations describe how modulational instability leads and develops in the system. By applying linear stability analysis (LSA) to the steady-state solutions,the modulational instability properties of the system are examined. The findings show that an imbalance between the Stokes and anti-Stokes components is caused by the SRS effect and the peak MI frequency shifts toward the Raman frequency. Furthermore, non-conventional MI sidebands appear in the normal dispersion regime. Self-induced transparency (SIT) makes the instability more stable and strongly suppresses it. when compared to standard optical fibres. These findings may help in the development of advanced optical fiber communication systems.

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Higher-Order Interaction Induced Transitions in Mixed Populations of Izhikevich Neurons

Soorya P P[1], Biswambhar Rakshit[1]

[1]Department of Mathematics, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham,Tamilnadu,India

We investigate the collective dynamics of mixed populations of excitable and self-oscillatory neurons described by the Izhikevich model, incorporating two different network structures and higher-order interactions. The study aims to understand how the interplay between neuronal heterogeneity and interaction structure shapes emergent behaviors such as synchronization, bursting, and metastability.

In an ensemble setting of all-to-all network, we first show that the coexistence of excitable and oscillatory units can give rise to robust oscillatory dynamics, including bursting and spike-adding phenomena. To gain insight into the underlying mechanisms, we analyze reduced models and identify bifurcation structures associated with the onset of bursting and aging transitions.

Extending this framework to random network topologies, we uncover a rich sequence of dynamical transitions driven by increasing higher-order coupling strength. Our results reveal a sequence of dynamical transitions from synchronized regular spiking to synchronized chaotic bursting, followed by a regime of fast chaotic spiking. The transition to chaotic bursting occurs via a spike adding route, while the subsequent transition to fast chaotic spiking is associated with the loss of the bifurcation structure responsible for burst termination, leading to the collapse of silent phases. We demonstrate that weak second order interactions support complete cluster phase synchronization in both excitable and self-oscillatory neuronal populations, whereas increasing higher order coupling induces a second order transition to partially synchronized dynamics. This partially synchronized regime is characterized by synchronized bursting and metastability. Further increase of second order interactions strength drives the network into a fully incoherent state characterized by irregular fast spiking. Additionally, we show that network link density strongly influences the degree of synchrony among self-oscillatory neurons but has limited impact on excitable neurons in the partial synchrony regime due to their heterogeneous firing rate distributions.

Dynamical Indicators of Critical Transitions in Astrophysical Systems

Devraj Pawar[1], Anisha Kashyap[2], G. Ambika[3], Ranjeev Misra[2]

[1]R. J. College, Ghatkopar (W), Mumbai-400086
[2]Inter-University Centre for Astronomy & Astrophysics, Pune-411007
[3]IISER, Thiruvananthapuram-695551

Complex systems often undergo changes affected by various factors, and their effects sometimes result in the transition of the system from one stable state to another stable state. For many systems, it is possible to detect early-warning signals before this critical transition.

Astrophysical systems are dynamic systems that evolve due to the various perennial physical processes within as well as with their interactions with other systems and also with the medium around them. Such astrophysical systems can exist for varying time spans in certain states, each characterized by a specific pattern of behavior indicated by its spectrum and variable luminosity. The evolution from one state to the other can occur on short time scales seen in gamma ray bursts or supernovae events or occur gradually as in the case of most neutron star and black hole X-ray binaries.

These states often correspond to different ranges or combinations of control parameter values whose information is embedded in the lightcurves of these systems. Control parameters play a crucial role in defining the state of the system and how it evolves, and sometimes a small change in a control parameter(s) causes the system to shift abruptly from one state to another; this is called a critical transition [1]. For example, in X-ray binaries the energy output across the energy spectrum can change by a few orders of magnitude [2] during outbursts, and the system exhibits well defined states based on spectral and temporal characteristics [3]. Often such critical transitions are preceded by changes in the system's behavior, which can be the "early warning signals" to such transitions. The observed changes may be indicators of critical changes in the system as seen in the recent historical dimming of Betelgeuse [4]. Lightcurves of astrophysical systems show variability characterized by various parameters, however, variability which will lead to critical changes will have different parameter values which can be calculated using Multi-fractal analysis and Recurrence Quantification Analysis. Predicting the outbursts of such transient systems based on lightcurves from monitoring instruments is an important aspect to study the evolution of their complex dynamics and to plan observations.

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Topology-Driven Mixing and Demixing of Knots in DNA

Garima Mishra*, Souradeep Sengupta

Department of Physics, Ashoka University, Sonipat, Haryana, India

At high salt concentration and elevated temperature, the persistence length of DNA decreases, enabling sufficiently long molecules to enter an effectively flexible-polymer regime capable of accommodating multiple knots along the same chain. Since enzymes such as topoisomerases recognize and act on local strand crossings, understanding the interaction, localization, and spatial organization of knots under mechanical tension is important for describing the knot topology of stretched biopolymers.

Previous studies have reported the formation of multiple knots in confined DNA chains [1], aggregation and localization of knots under stretching and confinement [2], and fluctuation-assisted knot-swapping mechanisms in stretched polymers [3]. Here, we investigate the tension-dependent mixing-demixing behavior of multiple knots on a stretched polymer using coarse-grained simulations. We compare polymers containing identical trefoil knots $(3_1 \otimes 3_1)$ with heterogeneous knot pairs $(3_1 \otimes 5_1)$. The applied tension is controlled through the normalized wall separation, which modifies chain alignment, configurational entropy, and knot localization dynamics.

Figure 1 shows the variation of average knot separation and knot size as a function of normalized wall separation for two temperatures[cite: 61]. For homogeneous trefoil pairs $(3_1 \otimes 3_1)$, the knot separation exhibits pronounced non-monotonic behavior with increasing tension[cite: 62]. At intermediate tension, enhanced longitudinal confinement promotes mixing through the swelling of one knot, allowing penetration of the second knot, as reflected in the knot-size variation (right panels)[cite: 63]. At larger tension, the knots tighten and transverse breathing fluctuations are suppressed, leading again to demixing[cite: 64]. Increasing temperature further enhances mixing in the homogeneous system.

In contrast, heterogeneous knot pairs $(3_1 \otimes 5_1)$ exhibit stronger mixing at low tension but progressively separate with increasing stretching force[cite: 66]. The larger 5_1 knot remains systematically more extended than the 3_1 knot, highlighting topology-dependent localization dynamics under confinement[cite: 13, 67]. Our results demonstrate that mechanical tension and temperature act as effective control parameters for regulating topological interactions in DNA-like polymers through the interplay of confinement, topology, and fluctuation-mediated knot dynamics.

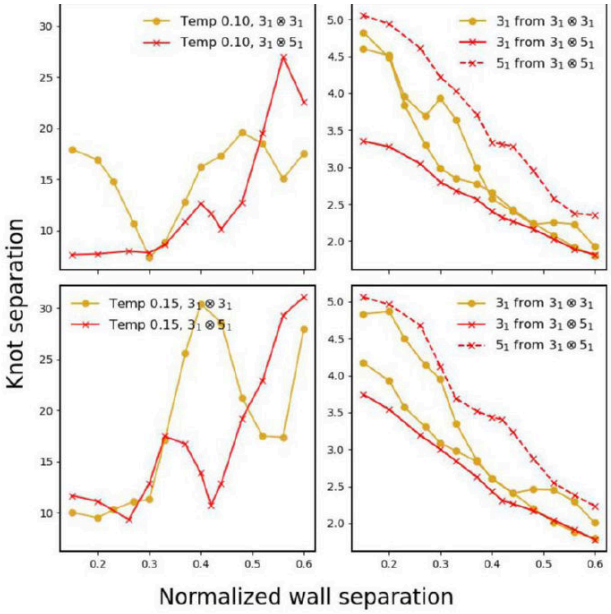

Figure 1: Tension-dependent mixing and knot size variation. Left panels: average knot separation versus normalized wall separation for homogeneous $(3_1 \otimes 3_1)$ and heterogeneous $(3_1 \otimes 5_1)$ knot pairs. Right panels: corresponding knot localization lengths. Homogeneous trefoil pairs exhibit non-monotonic mixing-demixing behavior, whereas heterogeneous knot pairs progressively demix with increasing tension

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Early Prediction of Information Cascades Using a Correlation-Guided Clustered Echo State Network

Hariharan Srinivasan[1], **Masoom Bhargava**[1], **Sayan Gupta**[1]

[1]The Uncertainty Lab, Department of Applied Mechanics & Biomedical Engineering, Indian Institute of Technology Madras, Chennai, 600036, Tamil Nadu, India

In online social network, information spreads rapidly such that a single post can propagate through multiple layers of user interactions leading to large-scale information cascades. As reported by Vosoughi et al. [1], these cascades can be characterized by several structural features including size, depth, breadth, and structural virality, each of which evolves over time and captures a distinct aspect of how information propagates through the network. Together, these features make cascade growth a multivariate temporal process. Accurate early prediction of these multivariate cascade characteristics is challenging due to the complex and dynamic nature of social interactions, but it remains crucial for identifying viral content and mitigating misinformation.

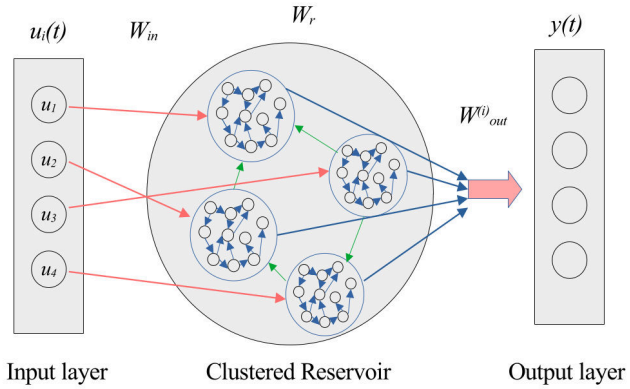

Figure 1: Schematic representation of CESN architecture [2]

Echo State Network (ESN), a subset of Reservoir Computing, offers an efficient alternative to conventional recurrent neural networks by training only the output weights, thereby reducing computational complexity. A recent variant, the clustered Echo State Network (CESN), is designed for multivariate time series prediction by organizing the reservoir into clusters corresponding to the number of variables to be predicted [2]. As illustrated in Fig. 2, the architecture consists of an input layer, a clustered reservoir, and an output layer. Each variable from a multivariate series is mapped to specific clusters in the reservoir, where intra-cluster connections remain dense while inter-cluster connections are sparse, mimicking the brain's modular organization. The outputs are trained only restricted to specific clusters using ridge regression, which reduces cross-variable interference and improves computational efficiency when modeling complex multivariate dynamics.

Despite its advantages, the degree of inter-cluster connectivity is determined through trial and error, which may lead to high error in predicting the ground truth. To address these limitations, an additional computational layer is introduced in the input stage that learns correlations among the input variables, enabling a data-driven coupling between clusters. During training, in addition to adjusting output weights, inter-cluster connection weights are trained, thereby enabling effective capture of cross-variable dependencies and improving prediction performance.

In this work, the improved CESN architecture is employed to predict the dynamics of information cascades in social networks. Early temporal features extracted from cascade evolution are used to represent multivariate variables, including cascade size, breadth, depth, and structural virality. These early-stage temporal features are mapped to corresponding clusters, and the data-driven correlation establishes inter-cluster connections. Hence, the proposed approach enables accurate prediction of final cascade growth patterns, providing a potential framework for anticipating and mitigating the spread of highly viral content, particularly misinformation.

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Synchronization of pulse-coupled oscillators in distributed power grid control

Ivan Sevostianov[1], **Pere Colet**[1], **Damià Gomila**[1]

[1]IFISC, Palma de Mallorca, Spain

High penetration of renewable sources makes the power grid more fragile by reducing the fraction of controlled production, and, in extreme cases, triggers large-scale blackouts. The conventional way of balancing grid operation frequency are production adjustments according to the changes in consumption. Control capabilities could be significantly expanded by adding smart circuits that react to frequency fluctuations to ordinary devices such as heaters, coolers, chargers, etc. Their operations can be postponed or advanced, respectively decreasing or increasing demand whenever needed, namely acting as a virtual energy storage. Yet, simple algorithms may lead to synchronization of the operation cycles when recovering pending tasks, eventually triggering large frequency fluctuations [1]. These smart devices are, in fact globally coupled via the grid frequency. For devices that can only be in one of two states - ON or OFF - the reaction generates a frequency pulse when changing states. Pulse coupled oscillators appear in biology[2], but, as opposed to those models, here interaction is not direct from one oscillator to another. Rather, it is mediated by the grid frequency, which depends also on conventional power plant controls. In particular for a simple model of a house with heat pump we find that frequency deviations trigger a reaction only if applied during a small fraction of the phase-space cycle. For several houses we find that this coupling favors a sort of anti-phase synchronization: houses gather in groups each consisting of two subgroups separated by a constant phase difference.

We use simulations of large oscillator ensembles to gather statistics about the stationary states they reach. With an insight from studying the behavior of oscillator pairs as dynamical system, we develop a method to detect groups of synchronized oscillators. Averaging over the initial conditions, we find a surprising result: probability distributions of group sizes have the same shape and scale linearly with the ensemble size N. With this in mind, we derive a convenient measure for coupling strength I that is independent of N. Synchronized groups produce simultaneous fluctuations in the grid frequency, thus by taking maximal group size for every stationary state (Fig. 2), we can infer the limits of control applicability. Besides, we obtain the mean fluctuation size as a function of coupling strength I for a small system, which in turn allows us to estimate the results for any N.

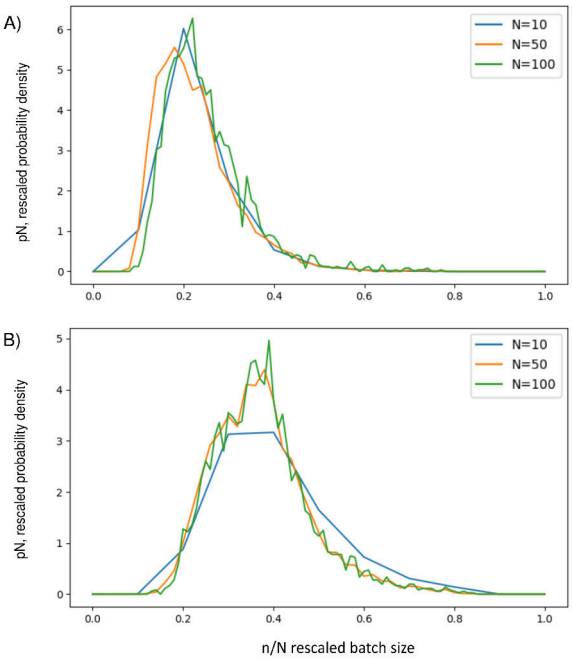

Figure 1: The probability distribution density of synchronized batch sizes, measured in the stationary state for $N = 10, 50$ and 100 heat pumps/oscillators and coupling strengths (A) $I = 5$, (B) $I = 10$. The plots are rescaled to conserve the property of PDF $\int pdx = 1$.

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Functional Network Topography reveal underlying non-linear dynamic changes to predict Depression.

Jasleen Gund[1]

[1]Amity Institute of Biotechnology, Amity University, Noida, India

Major Depressive Disorder (MDD) is a global health crisis that affects an estimated 280 million individuals, thus, making it a primary contributor to worldwide disability and disease burden. Its heterogeneous symptoms and dependence on subjective clinical assessments often lead to misdiagnosis and delayed intervention, highlighting the urgent need for objective neurophysiological biomarkers. Resting-state EEG provides a non-invasive and cost-effective tool to examine the altered temporal dynamics and disrupted network organization underlying MDD [1]. In this study, we present an EEG-based framework that integrates measures of signal complexity with functional brain network topology as features to distinguish MDD patients from healthy controls. Using the MODMA dataset containing high-density resting-state EEG recordings of 128 channels [2]. We estimated the hurst exponent across channels in the frontal, temporal, parietal and occipital region to characterize long-range temporal dependencies. We applied the Visibility Graph Approach (VGA) to construct networks from the EEG time-series to further assess underlying network-level topographical changes in functional connectivity [3]. The results demonstrated changes in degree, clustering coefficient, eigenvector centrality, and participation coefficient in MDD patients. Moreover, Hub classification revealed a reorganization of topological roles, with identification of connector hubs. The result as shown in Figure 1, suggest that connector hubs in the frontal and parietal region play a central role in global connectivity also consistent with the changes observed in spectral power and complexity. Our integrated analysis of resting-state EEG in MDD reveals that the disorder is marked by both altered temporal dynamics and disrupted network topology. Further we used this feature set to train machine learning algorithms to predict depression from healthy individuals. Overall, our findings underscore the potential of EEG-derived complexity measures and hub metrics as promising objective signatures for characterizing MDD-related brain dysfunction and advancing neurophysiological markers.

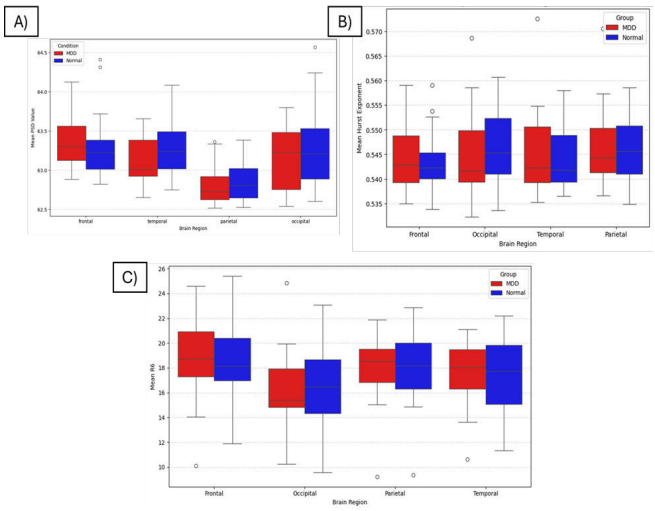

Figure 1: Region-wise comparative analysis plots of (a) Power Spectral Density (PSD), (b) hurst exponent, and (c) Connector Hubs (R6) among Major Depressive Disorder (MDD) and Healthy Control (HC) groups.

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Theoretical measures of species persistence

Jayant Pande[1]

[1]FLAME University, Pune, India

How persistent is a species in a particular ecosystem? This is a vital question in ecology, conservation and allied fields, and its analysis is made hard by the fact that real ecosystems are inevitably under the effect of stochasticity.

This stochasticity is broadly of two kinds. Demographic stochasticity affects individual members of a population and results in a contribution to the population variance that varies linearly with the population size n. In contrast, environmental stochasticity affects the entire population coherently and provides a contribution to the population variance proportional to n^2. The species under interest may then be modelled as executing a random walk along the population axis, which allows some important persistence metrics, namely the mean time to extinction and the chance of invasion of the species, to be represented as the mean exit time and the exit probability of the random walk, respectively.

While the above picture is straightforward, the dynamics of a given system are generally too complex to allow a direct derivation of the exit times and exit probabilities, and as a workaround one approach that has been widely adopted in the literature is the use of the "invasion growth rate" IGR as a proxy for persistence metrics. The IGR measures how quickly a species grows on average when its abundance is low and all the other species in the system are at their equilibrium densities.

Despite its very widespread use in ecological literature, the IGR has several important limitations. In past work [1] we have demonstrated how employing the IGR as a quantitative indicator of properties like the mean time to extinction and the chance of invasion can lead to entirely false results. This problem is exacerbated when temporal abundance fluctuations lead to an increase in the IGR.

To overcome this problem, I present some analytical formulae we have derived for the chance of invasion of a species given small or large fluctuation amplitudes, and small or large fitness differences between species. These formulae, which supersede previous Fokker-Planck-equation-based approaches, are rooted in the large-deviations WKB approximation, and lead to results that are independent of the particular model dynamics in operation in a given system, as long as the focal population is assumed to be in the invasion regime, i.e., to have a low population. The use of the formulae requires only parameters that may be easily ascertained from a time series of the focal species population when it has a small size.

I then present our analytical results for the mean time to extinction of a species in a fluctuating environment. Because the focal species may now start from a bulk population, the assumption of the invasion regime no longer holds, which means that the system may have complicated states such as attractive fixed points pertaining to coexistence. In this case, I discuss how we work around attractive fixed points to obtain results whose scaling behaviour as a function of the system size matches the behaviour of the mean time to extinction found in Monte Carlo simulations.

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Self similar wave propagation in a tapered nonlocal nonlinear medium

M.S.Mani Rajan[1]

[1]Anna University, University College of Engineering Ramanathapuram 623513

Generation and manipulation of self-similar waves in a nonlinear nonlocal media are receiving a huge attention among researchers due to its potential applications in photonics [1]. The study of self-similar phenomena is crucially important as it revealed a variety of novel dynamical behaviours not found in homogenous nonlinear optical systems. We attain self-similar solution for a nonlocal nonlinear Schrödinger model using similarity transformation.

$$i\frac{\partial q}{\partial Z}+\frac{D(Z)}{2}\frac{\partial^2 q}{\partial t^2}+R(Z)|q|^2q$$
$$+S(Z)q\frac{\partial^2(|q|^2)}{\partial t^2}+\frac{F(Z)t^2}{2}q=i\frac{G(Z)}{2}q \qquad (1)$$

Where $D(Z)$ represents the GVD coefficient, $R(Z)$ is the coefficient of cubic nonlinearity, $S(Z)$ denotes nonlocality coefficient,$F(Z)$ is the tapering function, and $G(Z)$ is the gain or loss coefficient. Since medium is inhomogeneous, all these coefficients are varying along the propagation distance. By applying similarity transformation [2], bright similariton solution obtained as follows.

$$q(z,t)=\frac{P}{W(z)}\sqrt{\frac{\gamma_1 D(z)}{\beta R(z)}}\,\mathrm{sech}(\mu\Theta)\,\exp\left[i\phi(z,t)\right] \qquad (2)$$

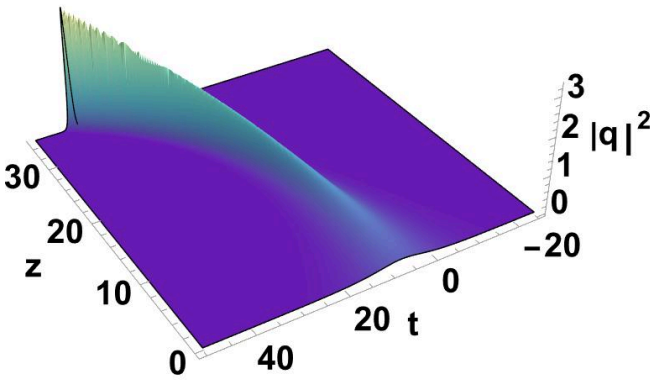

Figure 1: Self similar wave propagation in a nonlocal medium.

The 3D evolution corresponds to self similar solution shows the similariton propagation in a nonlocal nonlinear medium as depicted in Figure (1). During the course of propagation, similariton evolve as a self similar wave with gradually incraesing amplitude and compressed width as clearly shown in the density plot. According to physical relevance, inhomoegeneous profiles of GVD, nonlinearity, width and tapering can be tailoring properly. Self similar soliton behaviour is essential for the construction of nonlinear photonic circuit.

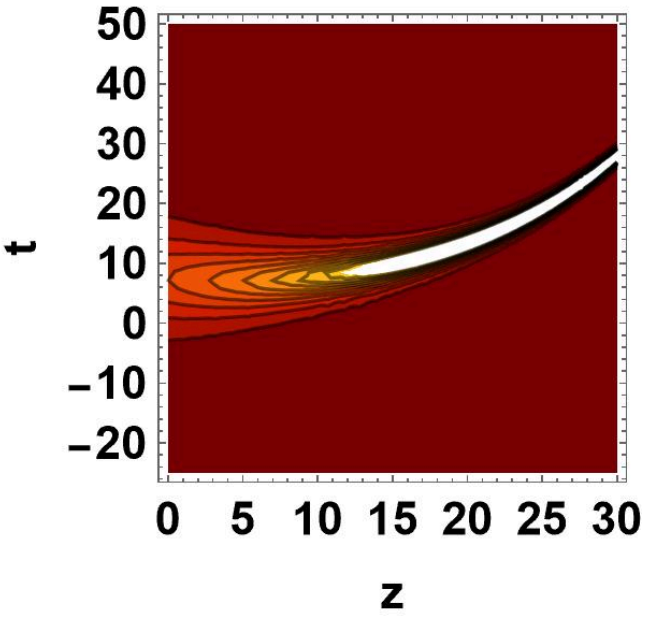

Figure 2: The density plot of the Figure(1)

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Collective dynamics of a minimal swarmalator model under external forcing

Md Sayeed Anwar[1], Dibakar Ghosh[2], Kevin O'Keeffe [3]

[1]Indian Institute of Science Education and Research- Kolkata, Campus Rd, Mohanpur, West Bengal 741246
[2] Indian Statistical Institute, 203 B. T. Road, Kolkata 700108, India
[3] Starling Research Institute, Seattle, Washington 98109, USA

We study a simple model of swarmalators subject to periodic forcing and confined to moving around a one-dimensional ring. This is a toy model of physical systems that combine sync, swarming, and forcing, such as colloidal micromotors. We find rich behavior (see Fig. 1): pinned states where the swarmalators are locked to the driving, sync states where their phases are either identical or have fixed differences, and unsteady states, such as swarmalator chimera, where the population splits into two sync dots enclosed by a "train" of swarmalators that run around a peanut-shaped loop. We derive the stability thresholds for most of these states, which gives us a good approximation of the model's phase diagram.

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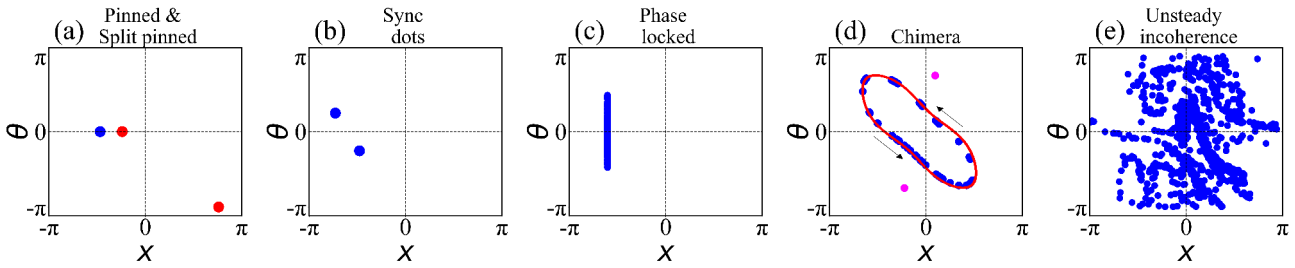

Figure 1: Collective states of the forced swarmalator model. (a) Pinned (blue dot) and split pinned (red dots) state, (b) Sync dots, (c) Phase locked state, (d) Chimera state, (e) Unsteady coherence state.

Understanding the Spread of True and False Information in Social Networks

Masoom Bhargava[1], **Hariharan Srinivasan**[1], **Sayan Gupta**[1]

[1]Department of Applied Mechanics and Biomedical Engineering, Indian Institute of Technology Madras, Chennai, India

The rapid spread of false information on digital platforms poses a serious challenge to public trust and democratic discussion. Although researchers often use traditional epidemiological models to study this issue, these approaches tend to simplify it by treating the spread of information in the same way as a biological virus[1]. This comparison fails to capture the complex psychological factors and network structures that actually influence how people share information.

To address this limitation, we propose a new mathematical framework that tracks the probability of individuals sharing true versus false news over time, supported by empirical data. In particular, the model allows us to examine how different factors influence the decision to share true versus false information. It incorporates key factors such as confirmation bias [2], the limited nature of human attention [3], and the effect of fact-checking interventions [4], that arises when individuals are exposed to conflicting information.

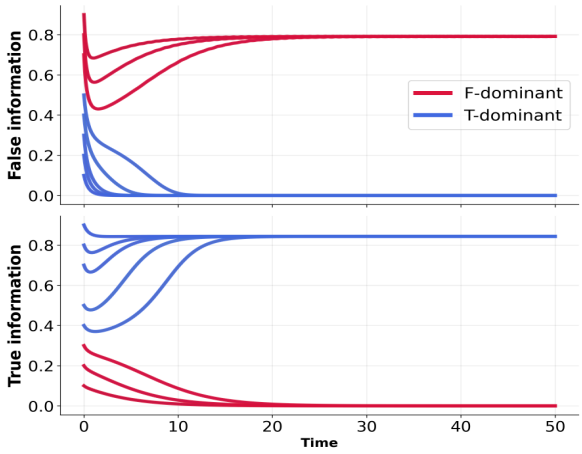

Figure 1: Initial Condition-Dependent Dominance of True and False Information

Instead of relying on simple population level averages, we combine these processes with a network-based diffusion mechanism to capture local patterns of social influence [5]. Using this approach, we demonstrate how the interaction between human behavior and network structure can create conditions that allow strong and persistent belief to form. As illustrated in Fig. 1, the spread of true and false information depends strongly on initial conditions, leading to different dominant outcomes. Overall, this framework bridges the gap between individual behavior and network structure. It provides a more realistic and systematic understanding of how misinformation spreads and why it is difficult to control.

Figure 2: Social network structure illustrating information diffusion (Source: IRW website, https://irw.co.in/)

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Multistability in Orthogonal Machining with Nonsmooth Frictional and Time-delay Effects

Meiyazhagan Jaganathan[1], **Vikram Pakrashi**[1], **Aasifa Rounak**[1]

[1]UCD Centre for Mechanics, Dynamical Systems and Risk Laboratory, School of Mechanical and Materials Engineering, University College Dublin, Ireland.

In machining, time delays arise from regenerative effects. Particularly in orthogonal cutting, the instantaneous chip thickness depends on the tool position at the current time and at one or more previous spindle revolutions. Also, cutting processes are inherently nonsmooth, with abrupt transitions due to stick-slip friction. The models used to analyze the stability of the machining process. Chatter, the back-and-forth vibration of a tool against the workpiece surface, is a major problem for stable machining. Yao *et al.* introduced a turning model with frictional and regenerative effects and further analysed it in deterministic and stochastic settings in Ref. [1]. The tool dynamics is modelled with damping c, stiffness k, and mass m, governed by

$$m\ddot{Y}(t) + c\dot{Y}(t) + kY(t) = F_f + F_d. \qquad (1)$$

where F_d is the process damping force and F_f is the feed force, depends on the instantaneous thickness of the chip $H(t) = H_D - Y(t) + Y(t - t_w)$ where H_D and $t_w = \frac{60}{N}$ are the feed rate and the rotational period of the workpiece, respectively. It also depends on the equivalent frictional coefficient, $\mu = \text{sign}(V_\gamma)\left(\mu_d + (\mu_d - \mu_s)\exp\left(-\frac{|V_\gamma|}{V_s}\right)\right)$, where V_s is the Stribeck velocity, μ_s, and μ_d are the static and dynamic friction coefficients respectively. $V_\gamma = V_{ch} - \dot{Y}(t)\cos(\gamma)$ represents the frictional velocity of the chip.

This model is improved by introducing a nonsmooth correction to the $H(t)$ to prevent negative values. The modified chip thickness is defined as $H(t) = H(t) \times \mathcal{H}(H(t))$, where $\mathcal{H}$ is the heaviside function. The results of linear stability analysis from numerical continuation show that the nonsmooth friction significantly shifts the stability lobes (SLD) as represented in Fig. 2.

Fig. 1 reveals two multistable regions, at depth of cut $a_p = 0.54\,mm$ and $a_p = 0.9\,mm$. Depending on the a_p value, the system exhibits (i) a stable fixed point, (ii) chatter without sticking, and (iii) chatter with sticking. The first multistable region (orange) contains fixed point and non-sticking limit cycles, whereas the second (blue) shows both sticking and non-sticking limit cycles.

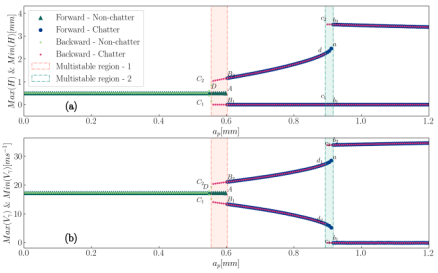

Figure 1: Bifurcation diagram using depth of cut a_p as the bifurcation parameter.

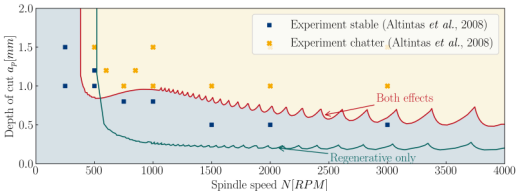

Figure 2: Stability lobe diagram.

In summary, this work demonstrates that the improved model generates a new multi-stable region in addition to the one previously reported. Numerical continuation provides an accurate SLD for such processes where frictional effects are considered. The results demonstrate that reliable chatter prediction requires a modelling framework that accurately captures both delay and nonsmooth tool-workpiece interactions.

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Existence and stability of wave solutions in the cubic-quintic-septimal nonlinear Schrödinger equation with spatially varying dispersion

Niladri Ghosh

Department of Physics, School of Physical Sciences, Amrita Vishwa Vidyapeetham, Coimbatore 641112, Tamil Nadu, India.

We investigate the existence and stability of multiple wave solutions of the cubic-quintic-septimal nonlinear Schrödinger equation with spatially varying dispersion[cite: 86]. The obtained solutions are classified into nontrivial-phase and trivial-phase categories[cite: 87]. In the nontrivial-phase case, only periodic wave solutions arise, expressed in terms of Jacobi elliptic functions[cite: 88]. In contrast, the trivial-phase case admits both periodic and localized structures, also constructed via Jacobi elliptic functions, with limiting cases reducing to solitary wave profiles described by trigonometric and hyperbolic functions[cite: 89].

A linear stability analysis is performed to examine the dynamical behavior of these solutions[cite: 90]. Analytical stability conditions are derived for periodic solutions in the trivial-phase case, while the remaining cases are analyzed numerically[cite: 91]. The stability is determined from the eigenvalue spectrum of the associated linearized perturbation equations[cite: 92]. Numerically, the eigenvalue problem is solved using a Fourier collocation method[cite: 83].

Furthermore, direct numerical simulations are carried out using a pseudospectral method in the transverse direction combined with a fourth-order Runge-Kutta scheme in the propagation direction, and are corroborated by results obtained via the Crank-Nicolson finite difference method[cite: 84]. These findings provide deeper insight into the formation and stability of nonlinear wave structures in inhomogeneous media, with potential applications in nonlinear optics, Bose-Einstein condensates, and wave propagation in complex dispersive systems[cite: 85].

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Unfolding the mystery of the complex biopolymer's stress response

Poulomi Sadhukhan[1]

[1]Bennett University, Greeter Noida, India

The intricate mechanical behavior[1] of biopolymer networks like fibrin is the result of several molecular-scale mechanisms that are triggered during deformation. We examine how fibrin fibers respond to stress concentrating on how mechanisms like molecular unfolding, entropic stretching and crosslink remodeling control their viscoelastic characteristics in various deformation regimes[2]. We demonstrate that crosslink remodeling is crucial in determining time-dependent responses especially stress relaxation[3] even though unfolding and stretching predominate at higher strains. According to our analysis slow relaxation modes are introduced by dynamic crosslink rearrangements resulting in long-lived metastable states non-exponential stress decay. Traditional linear viscoelastic models are unable to adequately represent these features[4, 5]. We also investigate the cause of the hysteresis seen when fibrin networks are cyclically loaded. We suggest that the observed hysteresis[6] is caused by different energy dissipation pathways created by partially irreversible crosslink remodeling in conjunction with molecular unfolding. This study provides new insights into the interplay between molecular mechanisms and macroscopic mechanical properties in complex biopolymer systems. Understanding these processes is essential not only for elucidating the fundamental physics of soft biological materials but also for designing biomimetic materials with tunable mechanical responses.

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Replicator-Mutator Dynamics on Networks with Spatial Nonlocality: Theory and Applications

Porikshit Mondal[1], **Ernesto Estrada**[1]

[1]Institute for Cross-Disciplinary Physics and Complex Systems (IFISC), CSIC-UIB, 07122 Palma de Mallorca, Spain.

The replicator-mutator model has been widely studied to understand the emergence of social norms and dominant behavioral patterns in social networks. In particular, it provides a framework to explain how "hubs" arise across diverse systems, including companies, politics, fashion trends, and celebrity influence. Within this setting, agents adapt their behaviors through interactions with others in the network, and such behavioral adoption is modeled through the combined effects of replication and mutation dynamics. The model exhibits a rich spectrum of evolutionary phases, including: (a) behavioral flocking, where a single dominant behavior emerges; (b) cohesion, characterized by a few dominant behaviors; (c) collapse, where many behaviors coexist; and (d) complete collapse, where no dominant behavior persists.

In the traditional replicator-mutator model, mutation spreads only through nearest-neighbor interactions, and the network's interaction structure is constructed accordingly. In realistic settings, however, agents are also influenced by others beyond their immediate neighbors, with the strength of influence typically decaying with distance. This motivates the question of how the evolutionary dynamics change when such nonlocal interactions are explicitly incorporated.

In this work, we investigate the role of long-range interactions within the replicator-mutator framework by introducing a generalized interaction structure based on the d-path Laplacian, which captures interactions across all hop distances within a single operator. We analyze how the strength of long-range coupling affects the system's evolutionary behavior across different network topologies. Notably, we observe that cultural globalization increases diversity while making behaviors more homogeneous. Our findings reveal several notable dynamical features, interpreted through spectral graph theory and stability analysis. The combination of analytical results and numerical experiments provides a comprehensive picture of how nonlocality reshapes the spectrum of possible behaviors, with direct applications to social dynamics, epidemic spreading, transport in infrastructure networks, and synchronization in biological and technological systems.

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From turbulence to graphs

Krishna Priya V. R.[1,2], Rinku Prajapathi [1,2], Snehal Sunil Patil [1,2], Rajaram Lakkaraju[1,2]

[1]Centre for Computational and Data Sciences, Indian Institute of Technology Kharagpur, West Bengal-721302, India
[2]TuRbulent Interfaces And Dispersion (TRIAD), Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal-721302, India

Why do turbulent systems suddenly reorganize into coherent structures, much like tipping points in climate and other complex systems? We explore this question using beta plane turbulence, a canonical model for planetary atmospheres and oceans. High-resolution simulations reveal that initially disordered turbulence spontaneously self-organizes into long-lived vortices and zonal jets through an inverse energy cascade. But how does one detect the emergence of this hidden order? To address this, we recast the evolving flow as a dynamic interaction network constructed from correlations in the vorticity field. Graph-theoretic measures, including modularity, clustering, assortativity, and path efficiency, serve as dynamical fingerprints of the flow, capturing abrupt reorganizations during vortex mergers and jet formation, while uncovering hidden transition pathways beyond the reach of conventional spectral analysis alone. Can such reorganizations be anticipated before they occur? Motivated by tipping phenomena, we develop a stochastic state space framework to quantify transitions between metastable turbulent regimes and the emergence of coherent order. Network-based diagnostics, particularly modularity, provide robust early-warning signals of impending regime transitions, significantly outperforming conventional variance- and autocorrelation-based indicators. Our results suggest that turbulence, despite its apparent randomness, evolves through identifiable and statistically predictable pathways toward large-scale self-organization.

Effects of Time Delay on Tunability in Andronov–Hopf Oscillators

Rakesh Kumar

School of Mathematical and Statistical Sciences (SMSS), IIT Mandi, Kamand - 175075, Himachal Pradesh, India.

Delay differential equations (DDEs) model systems in which the present state depends on past states, leading to rich dynamical phenomena such as oscillations, instability, and bifurcations. In contrast to ordinary differential equations, delays introduce an infinite-dimensional structure and can significantly alter system behavior.

In this talk, we investigate the role of time delay in oscillatory systems undergoing Andronov–Hopf bifurcation. Considering the normal form with delayed feedback, we show that delay can act as a bifurcation parameter, leading to the emergence of multiple Hopf bifurcations.

A key outcome is that the resonance frequency of the system becomes tunable through delay and feedback parameters. In particular, the frequency can be both increased and decreased, providing a flexible mechanism for controlling oscillatory dynamics. Numerical results illustrate the different dynamical regimes and validate the analytical findings. These results highlight the constructive role of delay and its potential applications in designing tunable oscillatory systems.

The Evolution and Formation of Indian Political Debate Networks

Satyam Mukherjee[1]

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

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, across all debates from 2010 to 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) [1] , 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.

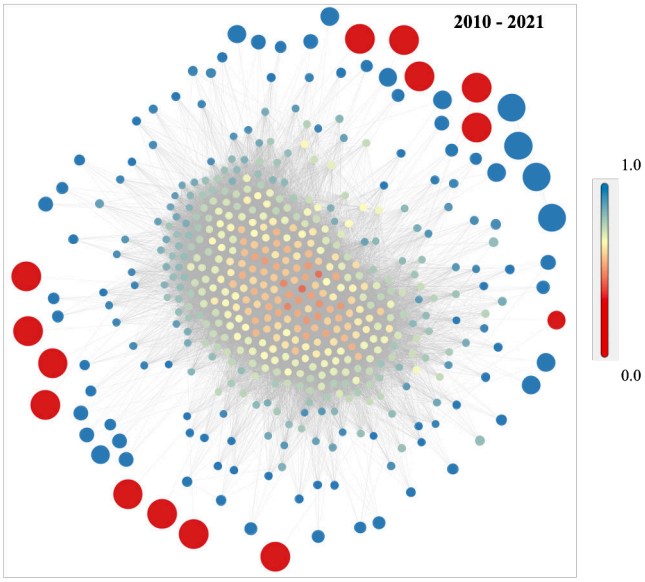

Figure 1: The network of debaters in the Rajya Sabha. Color: Local clustering coefficient. Size: Burt's constraint

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

$$\begin{aligned}\Pr(Y=y) = \frac{h(y)}{\kappa}\exp\Big[&\theta_1\,\text{NonZero}(y,x)+\theta_2\,\text{Sum}(y,x)\\&+\theta_3\,k_{\text{core}}(y,x)+\theta_4\,\text{Constraint}_{\text{Burt}}(y,x)\\&+\theta_5\,\text{LCC}(y,x)+\theta_6\,\text{Nodefactor}_{\text{Gender}}(y,x)\\&+\theta_7\,\text{Nodematch}_{\text{Gender}}(y,x)+\theta_8\,\text{Nodefactor}_{\text{HighestDegree}}(y,x)\\&+\theta_9\,\text{Nodematch}_{\text{HighestDegree}}(y,x)\Big] \quad (1)\end{aligned}$$

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 ($p<0.001$), whereas the effect for Post Graduates is weakly significant ($p<0.05$). 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 significant differences were 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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Symmetry Breaking in Biological Systems: From Pattern Formation to Chromosome Inactivation

Shibashis Paul[1], **Tian Hong**[2]

[1] Department of Chemistry, National Institute of Technology Sikkim
[2] Department of Biology, University of Texas Dallas

Symmetry breaking is a ubiquitous principle in natural phenomena, fundamentally governing the development and function of biological systems. This talk will explore two distinct yet equally pivotal manifestations of symmetry breaking.

First, we will delve into novel insights regarding Turing pattern formation within biochemical reaction networks. Our recent work demonstrates that these intricate spatial patterns can emerge even in the absence of conventional feedback mechanisms, a departure from classical understanding [1]. These findings are highly pertinent to deciphering the complexities of tissue morphogenesis and hold significant promise for guiding the future synthesis of biological Turing patterns, a grand challenge in synthetic biology.

Second, we will shift focus to a critical epigenetic process: X-chromosome inactivation (XCI) during female embryogenesis. We will present a continuum reaction-diffusion model specifically developed to unravel the dynamic spread of gene silencing across the chromosome [2]. This model illuminates several crucial aspects of XCI, particularly highlighting the intricate interplay of feedback loops influenced by neighbouring histone markers and the essential regulatory roles played by PRC2 proteins in orchestrating the silencing process. Together, these studies underscore the profound and diverse influence of symmetry breaking in shaping biological complexity.

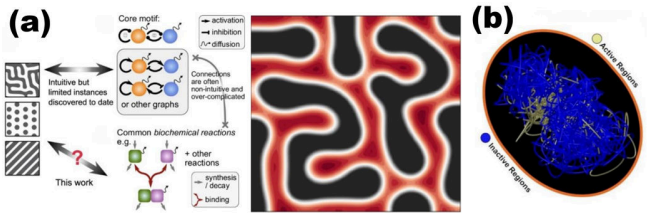

Figure 1: **(a)** Schematic representation of pattern formation without imposed feedback; **(b)** Inactive X chromosome.

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Beating solitons in the two-component nonlinear Schrödinger system

S. Stalin[1], S. Murugesh[1], M. Senthilvelan[2], M. Lakshmanan[2]

[1] Department of Physics, Indian Institute of Space Science and Technology, Valiamala, Thiruvananthapuram - 695547, India
[2]Department of Nonlinear Dynamics, Bharathidasan University, Tiruchirappalli - 620 024, India

It is well known that linear superposition of two waves with slightly different frequencies produces beats, arising from alternating constructive and destructive interference and characterized by a distinct beating frequency and beating period. From the perspective of nonlinear dynamics, a natural question arises as to whether soliton-supporting nonlinear systems can exhibit such beating phenomena. The answer is affirmative: such a beating effect can indeed be generated by utilizing the specific symmetry properties of a coupled system in nonlinear media, by using bright and dark solitons with different frequencies. The pattern arising from this procedure is referred to as beating solitons. This novel class of solitons has been generated by different methods and has been observed experimentally in Bose-Einstein condensates [1]. However, it has not been, or has been only scarcely, studied in nonlinear optics. The main purpose of this presentation is to point out the existence of beating optical solitons in a 2-coupled nonlinear Schrödinger system and to discuss their collision and stability dynamics.

To demonstrate this, we consider the two-coupled nonlinear Schrödinger equation of the form

$$i\psi_{j,t} + \psi_{j,xx} + 2\sum_{k=1}^{2}\sigma_k|\psi_k|^2\psi_j = 0,\ j = 1, 2, \quad (1)$$

where ψ_j denotes the complex amplitude of the jth component, while the independent variables t and x represent the normalized distance and retarded time, respectively, in nonlinear optics. The real constants σ_k determine the strength of the nonlinearities in the model (1). The coupled equations in Eq. (1) are invariant under SU(2) rotations:

$$\begin{pmatrix}\psi_1'\\ \psi_2'\end{pmatrix} = \begin{pmatrix}\alpha & \beta\\ -\beta^* & \alpha^*\end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix},\ |\alpha|^2 + |\beta|^2 = 1, \quad (2)$$

for $\sigma_1 = \sigma_2 = \pm 1$. Here ψ_j's are the bright and dark mixed soliton solutions of the system (1). For instance, mixed bright-dark one-soliton solution of the system (1) is given by

$$\psi_1 = A_1 e^{i\eta_{1I}}\text{sech}\Gamma_1,\ \Gamma_1 = k_{1R}(x - 2k_{1I}t + \frac{R}{2k_{1R}}),$$
$$\psi_2 = -a_1 e^{i(\theta_1+\rho_1)}[i\sin\rho_1 + \cos\rho_1\tanh\Gamma_1], \quad (3)$$

where $\eta_{1I} = k_{1R}x + (k_{1R}^2 - k_{1I}^2 + \lambda)t$, $A_1 = \frac{\alpha_1^{(1)}}{2}e^{\frac{-R}{2}}$, $e^R = \frac{\sigma_1|\alpha_1^{(1)}|^2}{(k_1+k_1^*)^2}\left[1 + \frac{\sigma_2|a_1|^2}{|k_1-ib_1|^2}\right]^{-1}$, $\rho_1 = \tan^{-1}(\frac{k_{1I}-b_1}{k_{1R}})$, $\theta_1 = b_1x - (b_1^2 - \lambda)t$, $\lambda = 2\sigma_2|a_1|^2$. The SU(2) rotated solution ψ_j' arising from the symmetry transformation (2), along with the solution (3), is referred to as a beating soliton. An interesting feature of the beating soliton is that it exhibits beating spatio-temporal oscillations in the individual components, as shown in Fig. 1, but no oscillations appear in the total density. When $k_{1I} = b_1$, the beating soliton exhibits a beating effect in the propagation direction, characterized by the period $T = \frac{2\pi}{k_{1R}^2}$, whereas for $k_{1I} = \sqrt{k_{1R}^2 + b_1^2}$ the beating effects appear in the temporal direction with period $T = \frac{2\pi}{|k_{1I}-k_0|}$. We have found that this new class of vector solitons undergo energy-sharing collisions and are stable against perturbations [2].

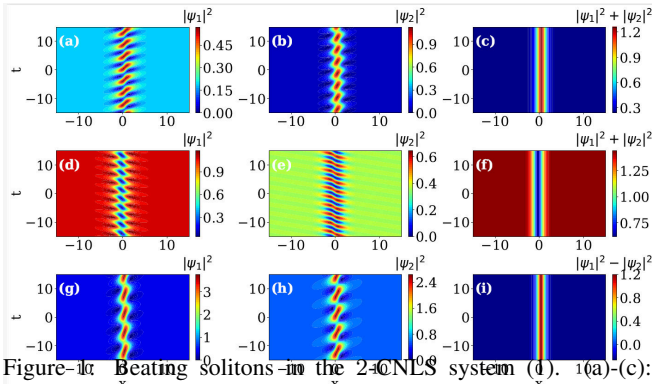

Figure-1: Beating solitons in the 2-CNLS system (1). (a)-(c): $\sigma_1 = \sigma_2 = 1$, (d)-(f): $\sigma_1 = \sigma_2 = -1$, (g)-(i): $\sigma_1 = -\sigma_2 = 1$.

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A Qualitative Study of Nonsmooth Dynamical Systems

Iguer L. D. Santos[1], Sanket Tikare[2], Bipan Hazarika[3]

[1]Universidade Estadual Paulista (UNESP), Faculdade de Engenharia, Ilha Solteira, Departamento de Matemática, CEP 15385-000, São Paulo, Brazil
[2]Department of Mathematics, Ramniranjan Jhunjhunwala College, Mumbai, Maharashtra 400 086, India
[3]Department of Mathematics, Gauhati University, Guwahati 781014, Assam, India

Dynamical systems whose associated vector fields admit discontinuities, arise in several applications, which can be witnessed by [1, 3, 5, 6, 7]. Such dynamical systems are known as nonsmooth dynamical systems (or discontinuous dynamical systems) and are often described by ordinary differential equations with discontinuous right-hand side, that is, by discontinuous differential equations. In this talk, we study the nonsmooth dynamical systems that are determined by differential equation

$$\dot{x}(t) = f(t, x(t)) \tag{1}$$

where $f : \mathbb{R} \times D \to \mathbb{R}^n$, $D \subset \mathbb{R}^n$ is a given open set with $0 \in D$, and the vector field f admits discontinuities.

In this work, we study the asymptotic behavior of solutions of discontinuous differential equations using the notions of Caratheódory and Krasovskii solutions. We establish stability and decay rate properties for discontinuous differential equations. In the literature on nonsmooth dynamical systems, there is a lack of results related to general decay rate for discontinuous differential equations. Hence, analogous to [4] and using nonsmooth Lyapunov functions, we establish results on decay rate of solutions of discontinuous differential equations. The study of the stability of nonsmooth dynamical systems can be carried out through the use of nonsmooth Lyapunov functions (see [2] and [8]). Thus, analogous to the Lyapunov direct method for continuous ordinary differential equations, we use the Lyapunov direct method for discontinuous differential equations. Hence, we establish stability properties for nonsmooth dynamical systems by using nonsmooth Lyapunov functions.

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The Role of Cell Volume in Non Linear Mathematical Models of Bacterial Growth

Shagun Nagpal Sethi[1], Sanjay Jain[1,2]

[1]Department of Physics and Astrophysics, University of Delhi, Delhi, India
[2]Santa Fe Institute, 1399, Hyde Park Road, Santa Fe, NM 87501, USA

A single cell of a bacterium, such as *Escherichia coli*, is a highly complex, non-equilibrium, non-linear, many-body system. It contains thousands of molecular species that participate in an intricate network of biochemical reactions, continuously exchanging matter and energy with the environment. Remarkably, despite this complexity, the intracellular chemical network operates in a highly coordinated manner to achieve growth, division and self reproduction of the bacterium. In particular, cells show phenomena such as balanced growth and exponential trajectories of cell size and of chemical populations which are particularly surprising in a non-linear system. Another notable feature is the set of bacterial *growth laws*, which describe how the ribosomal protein fraction varies with growth rate of bacteria.

These regularities can be understood through coarse-grained mathematical models of coupled, non-linear, ordinary differential equations describing the chemical dynamics within a growing container. Most studies of chemical dynamics are typically carried out in a fixed size container or in containers whose time dependent volume $V(t)$ is specified exogenously. However, the volume of a cell should depend upon the chemical populations it contains. It has been shown that when the volume of this container is defined endogenously as a homogeneous degree one function of the intracellular chemical populations X_i (in particular, as a linear function $V = \sum_i v_i X_i$, where the coefficients v_i are constants), the non-linear system displays a *scaling property* and exhibits balanced growth and exponential trajectories [1]. These outcomes are obtained irrespective of the specific choice of coefficients v_i.

In the present work [2], we investigate the role of the volume definition in explaining the *growth laws*, specifically we focus on the dependence of *growth laws* on the coefficients v_i, which has not yet been explored. Our analysis shows that both the growth rate and the steady state concentrations of the internal chemicals depend on the particular choice of the coefficients v_i. Certain choices successfully reproduce the observed bacterial *growth laws*, while others fail to do so. In particular, a choice of coefficients which results in constant density across growth rates, fails to reproduce the bacterial *growth laws*.

These findings suggest that the functional form of the volume definition imposes strong constraints on bacterial physiology. Consequently, experimental as well as theoretical efforts aimed at determining the coefficients v_i could provide important insights into the physical principles governing cellular growth.

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Spatial synchrony at the extremes: Tail-dependence in temperature drives tail-dependence in birds' spatial synchrony across North America

Shyamolina Ghosh[1,2], Owen L. Petchey[2]

[1]Indian Statistical Institute, Kolkata, India
[2]University of Zurich, Zurich, Switzerland

Many spatially distributed dynamical systems show synchrony, meaning that variables at different locations fluctuate together over time. Synchrony is usually measured using correlation, which captures dependence near average values but may miss dependence during extreme events.

Understanding how climatic extremes influence spatial synchrony is crucial for predicting biodiversity responses to global change. We test whether spatial synchrony in bird abundances exhibits tail-dependence (i.e., dependence concentrated in extreme low or high values), and whether tail-dependent synchrony in climatic extremes explains these patterns.

We analyzed North American breeding bird abundances (1979–2019) together with temperature and precipitation time series at survey locations. For pairs of sites within 250 km, we first quantified overall synchrony using rank correlation on detrended time series. We then quantified synchrony at the extremes using copula-based tail-dependence via partial Spearman correlations in the lower and upper tails of the joint rank distribution[1].

Across multiple minimum time spans (32, 36, and 40 years), many species showed significant spatial synchrony, and a consistent subset exhibited significant tail-dependent synchrony. Tail-dependent synchrony in precipitation and temperature strongly predicted tail-dependent synchrony in abundance across species, explaining up to 86% of the variation, supporting an extension of the "Moran effect"[2] to extremes. Phylogenetic regression confirmed climate as the dominant driver, while dispersal ability (as measured by the hand-wing index) was generally non-significant. Directional analyses gave limited support for asymmetry: higher temperatures tended to increase upper-tail synchrony, whereas cooler conditions promoted lower-tail synchrony; precipitation showed no clear directional effect.

Our results show that climatic extremes can propagate into population dynamics through tail-dependent spatial synchrony, highlighting the importance of long-term, large-scale monitoring and nonlinear dependence measures for assessing vulnerability under climate change.

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Multistability and tipping in a conceptual model of the subpolar gyre (SPG)

Sneha Kachhara[1], Paul Ritchie[1], Peter Ashwin[1], Anna von der Heydt[2], Henk Dijkstra[2]

[1]University of Exeter, Exeter, United Kingdom
[2]Utrecht University, Utrecht, the Netherlands

The climate of northern Europe and the British Isles is influenced by North Atlantic ocean circulation, especially the subpolar gyre (SPG). Along with the Atlantic Meridional Overturning Circulation (AMOC), multistability in the SPG is often observed in complex Earth system models (ESMs) such as those considered in the CMIP6 runs [1]. This multistability corresponds to different circulation regimes, broadly classified into strong (current) and weak regimes. The weaker circulation is associated with the collapse of deep convection and a shallow mixed-layer depth. Studies indicate that these systems may already be en route to these (undesirable) alternate states, making them important tipping elements [2].

To better understand these tipping elements and their dynamics, conceptual low-dimensional models have been proposed. Some of these models capture deep convection process in the SPG and find that to be strongly related to its overall circulation strength [3]. Most such models exhibit bistability but lack the metastable states observed in more complex models. This poses a challenge for designing early warning systems or adaptation strategies based on low-dimensional tipping behaviour, particularly if such metastable states are realised in practice. Since these models nevertheless capture the essential dynamics of the system, an important question arises: how do these metastable states originate in higher-dimensional representations?

Previously den Toom et al. [4] investigated this phenomenon with the help of a generalized water column model for deep convection. They found a number of spurious equilibria inherent to a discretised convective adjustment. Here, we extend the model for deep convection in the subpolar gyre (SPG). We incorporate the influence of boundary currents on the central basin that shed eddies into the central column, moderating its temperature and salinity (see fig. 1). This model captures the essential dynamics of low-dimensional approaches while adopting a discretisation framework similar to higher-dimensional representations. We find that this model exhibits multistability. Specifically, the number of saddle-node bifurcations increase as the resolution increases, suggesting that some of these might be spurious. Given the similarity of this framework to that used in comprehensive Earth system models, our results suggest that some reported metastable states there might have a similar origin.

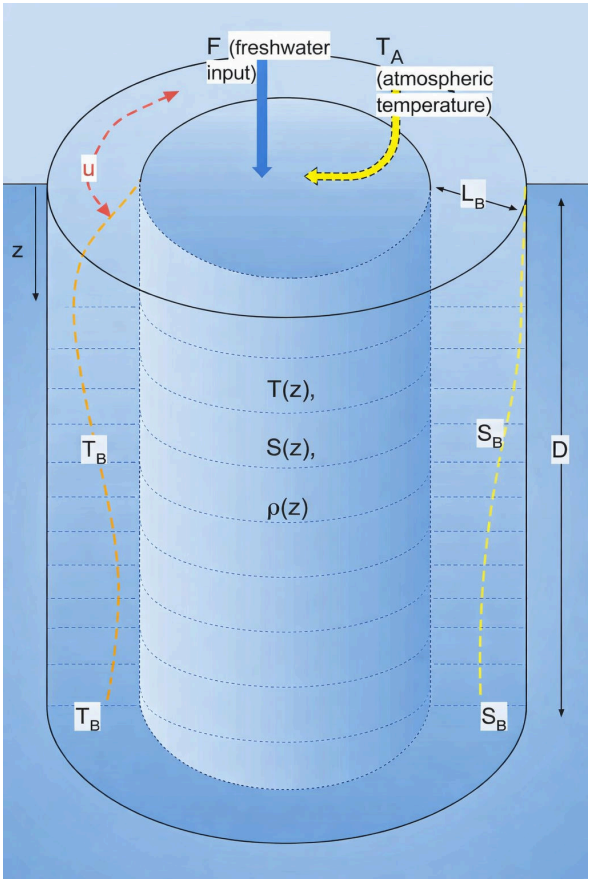

Figure 1: Schematic representation of the vertical column model for convection in the subpolar gyre (SPG). The central basin receives freshwater (F) and exchanges heat with the atmosphere (T_A is the atmospheric temperature).

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Binomial Maps: A bridge between stochastic agent-based models and deterministic integer-valued iterated maps

Snehal M. Shekatkar

FLAME University, Pune, India

Iterated maps are widely used objects to model a large number of real-world systems. A class of maps tries to model systems related to population dynamics. For example, the Logistic map is used to model the dynamics of population of a species with limited amount of resource. In such maps, the dynamical variables are fundamentally integers as they represent the number of individuals of some kind. However, their deterministic nature cannot model the stochastic fluctuations inherently present in population systems, especially when population size is small. In this low population limit, one must then use agent-based models which are capable of correctly modelling stochasticity in these systems at the expense of computational efficiency. Here we propose *Binomial Maps* as a bridge connecting these two formalisms. Binomial maps are stochastic maps that reproduce the behavior of agent-based models while remaining computationally efficient, and under some mild conditions, converge to deterministic maps' output in the limit of large population. Here we demonstrate this using the Logistic map as a test case.

Consider the Logistic map with carrying capacity K:

$$X_{t+1} = \mu X_t \left(1 - \frac{X_t}{K}\right) \tag{1}$$

The corresponding Logistic map assumes that X_t only determines the *expected value* of X_{t+1}, instead of directly determining X_{t+1}. The actual value of the number of individuals is then sampled from the Binomial distribution with this mean. Thus the corresponding Binomial map takes the form:

$$\begin{aligned} \mathbb{E}[X_b(t+1)] &= \mu X_b(t)\left(1 - \frac{X_b(t)}{K}\right) \\ X_b(t+1) &\sim \text{Binomial}\left(K, \frac{\mathbb{E}[X_b(t+1)]}{K}\right) \end{aligned} \tag{2}$$

where $\mathbb{E}(X)$ denotes the expected value of X. The behavior of the Binomial Logistic map for various values of the carrying capacity K is shown in the figure below:

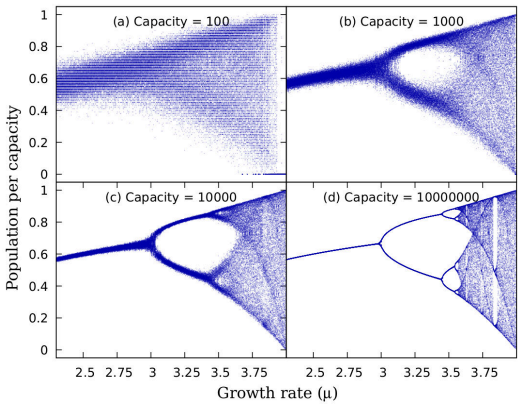

Figure 1: The bifurcation diagram of the Binomial Logistic map for four different capacities. As can be clearly seen, the bifurcation diagram approaches the bifurcation diagram of the standard Logistic map as the capacity increases.

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Experimental evidence of double explosive synchronization

Taniya Khatun[1,2], Md. Sayeed Anwar[1], P. Parmananda[1]

[1]Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
[2]Department of Mathematics, Indian Institute of Technology Ropar, Rupnagar, Panjab 140001, India

Explosive synchronization (ES) is characterized by irreversible transitions to collective coherence in coupled oscillator networks. Recent study *Phys. Rev. Research 4, 033009 (2022)* has predicted a richer phenomenon, double explosive synchronization (DES), in which a multilayer system exhibits two consecutive discontinuous transitions. Experimental evidence of DES, however, has remained lacking. Here we report the experimental observation of DES using multilayer networks of Wien-bridge oscillators. By coupling a strongly synchronized low-frequency driving layer to a weakly synchronized high-frequency controlled layer and gradually varying the interlayer coupling, we observe two distinct hysteretic transitions accompanied by bistability. Complementary LTspice circuit simulations reproduce the experimental behavior. These results establish DES as a robust and physically realizable phenomenon in multilayer oscillator networks.

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Dynamics of adaptive network with connection delay and external stimulus

S. Thamizharasan[1], V. K. Chandrasekar[2], M. Senthilvelan[1], D. V. Senthilkumar[3]

[1]Department of Nonlinear Dynamics, School of Physics, Bharathidasan University, Tiruchirappalli - 620024, Tamil Nadu, India.
[2]Centre for Nonlinear Science & Engineering, Department of Physics, School of Electrical & Electronics Engineering, SASTRA Deemed University, Thanjavur -613 401, Tamil Nadu, India.
[3]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram-695 551, Kerala, India.

Adaptive networks, wherein connection weights coevolve with nodal dynamics, have emerged as a powerful framework for understanding complex collective behaviors in neuronal, climate, and other real-world systems. The framework of adaptive networks is originally inspired by the pre- and postsynaptic firings of neuronal connections, wherein the synaptic strength increases or decreases based on the in-phase or out-of-phase firing of neurons, known as the Hebbian or anti-Hebbian learning rule. Despite extensive investigations into adaptive networks, the interplay between connection delay and adaptation rules remains less understood. Connection delay is an intrinsic neurophysiological feature arising from finite signal transmission speeds along neuronal axons - experimentally measured to be of the order of 1 m/s in unmyelinated fibers, resulting in delays up to 80 ms in cortical networks. In this work, we address this gap by investigating a globally coupled adaptive network of identical Kuramoto phase oscillators with Hebbian adaptation, connection delay, and external stimulus. We show that the adaptive network exhibits a rich variety of dynamical states, including antipodal, solitary, double antipodal, splay, multi-cluster, synchronized and force entrained states in the phase diagrams. In particular, we elucidate the delay induced double antipodal state in the adaptive network in the absence of the phase lag parameter. Further, we observe the solitary state in the globally coupled adaptive network for the first time in the literature. We corroborate the dynamical state and elucidate their dynamical transitions using the Kuramoto order parameters and the strength of incoherences. We also show that the network exhibits a rich variety of multistable states as a function of the system parameters. We also elucidate that the distance dependent delay facilitates the manifestation of similar dynamical states as that of the constant delay. Further, we show that the stability condition for the forced entrained state turns out to be the existence condition for the same, which agrees well with the simulation results.

These results significantly deepen our understanding of adaptive networks operating under neurophysiologically realistic conditions and open new directions toward heterogeneous frequency distributions, multilayer adaptive networks, and diverse structural topologies.

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Posters

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High-order synchronization in identical neurons with asymmetric pulse coupling

Abhay[1], Gaurav Dar[2]

[1,2]Department of Physics, BITS Pilani K K Birla Goa Campus, Zuarinagar, Goa-403726

High-order (p/q) frequency locking—in which one oscillator completes p cycles for every q cycles of another—has long been understood to require a frequency mismatch between the two oscillators as a strict prerequisite [1]. We counter this established picture: coupling asymmetry alone is sufficient to produce high-order synchronization, even when the oscillators are intrinsically identical [3]. This reveals a new route to a phenomenon previously thought to be inaccessible without frequency difference

Specifically, we study an excitatory-inhibitory pair of leaky integrate-and-fire neurons with identical intrinsic frequencies coupled asymmetrically. Building on this, we develop a new analytical framework for determining the existence and stability of p/q frequency-locked solutions and their underlying bifurcations—moving beyond existing methods, which rest on assumptions of non-identical neurons and weak coupling [2].

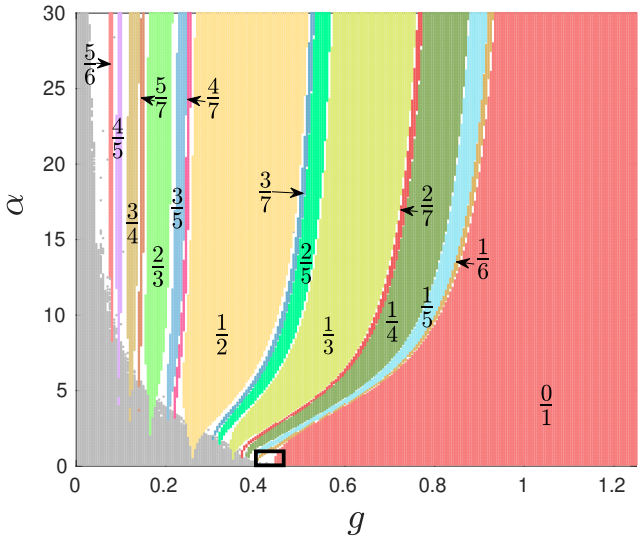

Figure 1: Dominant frequency-locked p/q regions and quasiperiodic region (shown in gray) in the (g, α) parameter space. Each color represents a distinct p/q frequency-locked region.

As shown in Fig. 1, systematic exploration of the synaptic strength (g) and inverse time constant numerous high-order frequency-locked regions descending from large to small values of α, with simple $1/1$ frequency locking being entirely absent under asymmetric coupling. Moreover, simulations display quasiperiodicity, devil staircase arrangement of p/q locking ratios, a novel Farey arrangement of spike sequences at large α. At smaller α, reducible np/nq frequency-locked islands emerge in ascending order of n, with mutual overlaps between family members.

Using analytical method we identify non-smooth grazing bifurcations (inaccessible to earlier analytical methods) — including two newly identified types — which govern the boundaries of frequency-locked regions alongside saddle-node bifurcations. Unlike the structureless Arnold tongues of forced oscillators, the p/q regions here possess internal structures which are formed largely by non-smooth bifurcations. These bifurcations create new solutions within a p/q region giving rise to intrasequence and intersequence multistability. These findings reveal that asymmetric coupling alone is sufficient to generate complex synchronization dynamics relevant to oscillatory activity in excitatory-inhibitory neural circuits.

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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

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, lag1 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.

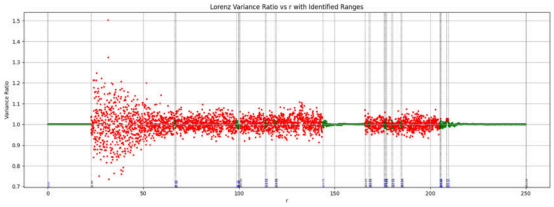

Figure 1: Identification of periodic windows in the Lorenz system using variance-based early warning analysis. The variance ratio metric (noisy-to-clean) reveals clear transitions between chaotic and periodic regions as the bifurcation pa- rameter r varies, demonstrating the sensitivity of variance as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

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Nonlinear Dynamics of Multi-Segment Chimney Models in Realistic Parameter Regimes

Adwait A. Kulkarni[1], **Sukruta A. Pethe**[1,2], **Kiran M. Kolwankar**[1]

[1]Department of Physics, Ramniranjan Jhunjhunwala College, Ghatkopar, Mumbai 400086, India
[2]Department of Physics, Sathaye College, Vileparle (East), Mumbai 400057, India

Wind-induced swaying of trees is frequently attributed primarily to turbulent aerodynamic forcing. However, the mechanisms governing the resulting dynamics understood largely by considering the linear stiffness of tree and wind turbulence. In this work, we investigate the interplay between stochastic wind excitation and intrinsic structural dynamics using a nonlinear multi segment chimney model as an representation of tree-like systems. The model includes cubic nonlinearity, damping, and periodic forcing [1, 2].

We first demonstrate that commonly used polynomial truncations of the gravitational restoring term can qualitatively alter system behavior, leading to incorrect predictions of effective stiffness and spurious dynamical regimes. Retaining the full nonlinear formulation reveals a consistent softening-type response and provides an accurate description of the underlying resonance structure. Under periodic forcing, multi-segment systems exhibit reverse period doubling cascades and localized chaotic regimes within experimentally relevant parameter ranges, whereas single segment models remain predominantly periodic.

In the absence of time dependent forcing, the deterministic system converges to a stable fixed point. However, the introduction of small noise in the system will leads to sustained oscillations. Analysis of experimental tree sway data supports this interpretation, while wind speed exhibits broadband turbulent spectra consistent with Kolmogorov scaling, the structural response displays frequency selective amplification with a dominant spectral peak and weak coherence with the input as shown in Fig. 1. Recurrence and cross-recurrence analyses further reveal structured dynamics and delayed coupling between wind and response.

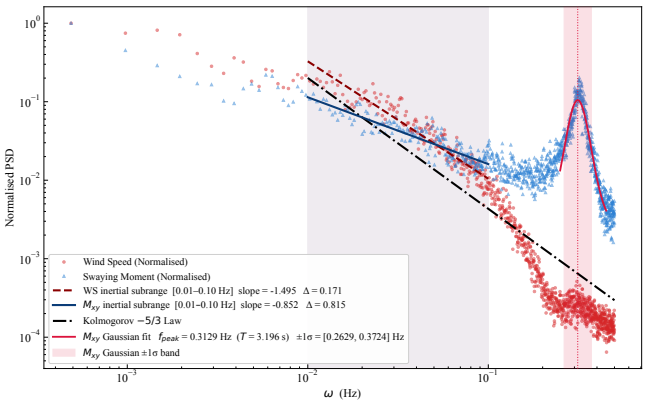

Figure 1: Power spectral density (PSD) of wind speed and swaying moment. The wind spectrum follows turbulent scaling ($\sim -5/3$), while the structural response deviates and exhibits a pronounced peak at ~ 0.31 Hz, corresponding to the natural frequency. This demonstrates frequency-selective amplification and the role of intrinsic structural dynamics.

These results suggest that wind-induced tree motion is not solely governed by external turbulence, but emerges from the interaction between broadband stochastic forcing and nonlinear structural dynamics. The proposed framework provides a unified interpretation of tree sway as a noise driven, multi-mode nonlinear oscillator, with implications for modeling wind structure interaction in both natural and engineered systems [2].

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Multiplicity vs Specificity: A Trade-Off in Multilayer Networks

Aradhana Singh[1], Amod Rai[2], Sheksha Dudekula [3], Devanarayanan P [4], Antonio Palacios [5]

[1]Department of Physics, Indian Institute of Science Education and Research, Tirupati, Andhra Pradesh 517507, India
[2]Department of Mathematics, San Diego State University, San Diego, USA

Multilayer networks provide a powerful framework for understanding complex systems where interactions occur across multiple layers. A fundamental question is how the nature of inter-layer connectivity influences emergent dynamics in non-identical networks. In this work, we investigate the trade-off between *specificity* (one-to-one inter-layer mapping) and *multiplicity* (one-to-many inter-layer connectivity), while keeping the total number of inter-layer connections fixed.

Using coupled Rössler oscillators, we show that specific inter-layer connectivity preserves intra-layer symmetry and robustly promotes intra-layer synchronization (ILS). In contrast, multiplicity introduced through random inter-layer connections breaks symmetry and gives rise to cluster synchronization governed by underlying graph homomorphisms. Furthermore, we demonstrate that amplitude death (AD) emerges at lower coupling strengths and smaller frequency mismatches in networks with specific inter-layer connectivity, whereas multiplicity delays the onset of AD.

We further find that symmetric inter-layer connectivity leads to size-independent AD regimes, while asymmetric connectivity introduces dependence on network size, topology, and density. Additionally, both connectivity schemes exhibit multistability and remnant synchronization, indicating memory-like behavior in multilayer systems.

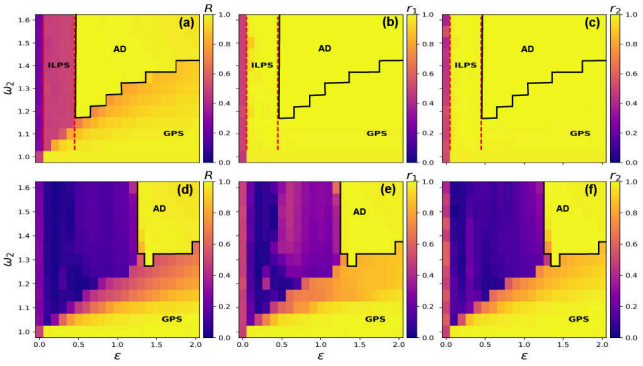

Figure 1: Parameter space for One-to-one and one-to-many inter layer connectivity

Overall, our results reveal a fundamental trade-off: specificity enhances synchronization and stability, while multiplicity improves robustness against amplitude death. These findings provide valuable insights into the design of multilayer networks with tunable dynamical properties.

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A Low Order Model for Thermoacoustic Instabilities in an Electrically Heated Annular Rijke Tube

Anirban Sadhukhan[1], Souranshu Roy Chaudhuri[1], Sourav Sarkar[1], Achintya Mukhopadhyay[1]

[1]Department of Mechanical Engineering, Jadavpur University, Kolkata, India

Thermoacoustic instability is a major challenge in combustion systems such as gas turbines, aeroengines and rocket engines, often leading to unstable operation and even catastrophic failures. The issue is particularly severe in rocket engines due to their confined geometry and extreme conditions. Experimental studies and simplified models provide qualitative insights but fail to predict quantitative measures like stability limits, while full-scale testing is expensive and risky. Hence, numerical simulation is widely used, though it remains challenging due to the coupling of acoustics, turbulence and chemical reactions across very different length and time scales. To address this, low-order models are employed, separating small-scale flame dynamics from the larger acoustic field. The interaction is captured through transfer or describing functions that link heat release fluctuations to flow perturbations. In this work, a low-order model of a Rijke tube is used. While it primarily captures longitudinal modes, real combustors also involve azimuthal and radial modes, along with injector - combustor interactions, which are incorporated using a configuration similar to Yoon's model. The acoustic model consists of the equations of conservation of mass, momentum and energy. Following Culick [2], the molecular diffusion terms are neglected. The wave equation is reduced to the well-known Helmholtz equation. First the dominant unstable modes are determined from the Helmholtz equation without the source term then the simulations are carried out in the frequency domain using commercial multiphysics software, COMSOL.

For electrically heated Rijke tubes, the heat source is a wire mesh carrying electric current. In the geometry simulated, there is an electric heater in each of the tubes. The heat release to the gas takes place by convection and is thus affected by the perturbations in the flow past the heated mesh. A high fidelity CFD simulation over a small domain in the vicinity of the heated wires provides the transfer function. The frequency domain study provides the complex eigenvalues corresponding to each mode of disturbance. The real part of the complex eigenvalue gives the modal frequency while the imaginary part gives the growth rate. A positive growth rate indicates unstable mode while a negative growth rate indicates a stable mode.

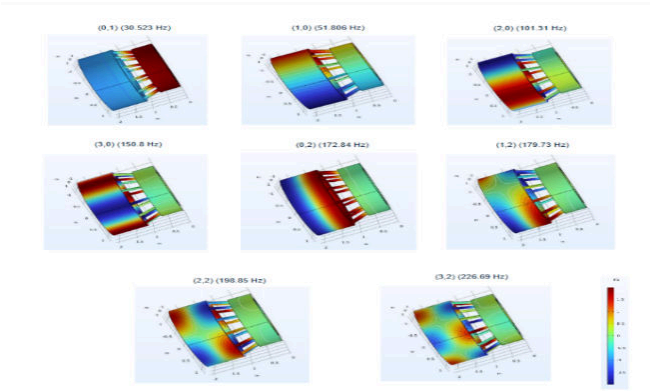

Figure 1: Pressure mode shapes of the (k,m) modes for k, m = 0, 1, 2, 3, 4, 5

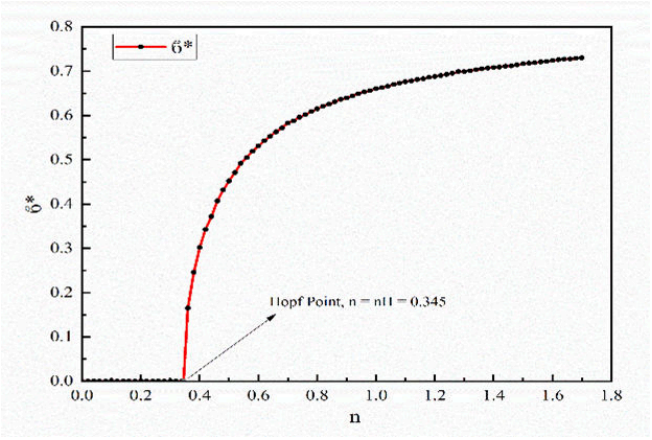

Figure 2: Bifurcation diagram of Rijke Tube describing oscillating condition

Fig. 1 shows the results for the annular domain only in absence of heat sources. The mode shapes of eigenfrequencies from 0 to 250 Hz has been done here and have been validated from Yoon[1] and Fig. 2 shows the bifurcation diagram of the Rijke tube obtained from the limit cycle, which is plotted under the condition that the time delay of the FDF τ is 8.2 ms, and a supercritical bifurcation presents. These results qualitatively match those results shown in Laera et al. [3].

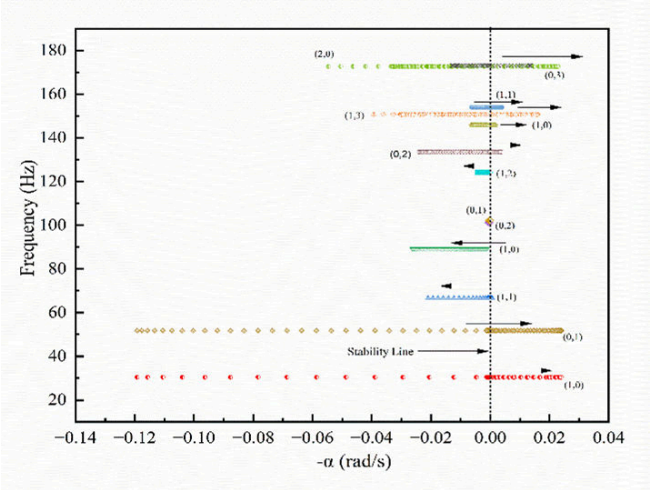

Figure 3: Combustion Instability Map

Fig. 3 presents stability maps over a time delay range of τ= 0 -11 ms, capturing the thermoacoustic response of an annular combustor for axially aligned and non-aligned (inclined) nozzle configurations which show that the axially aligned configuration remains largely stable across τ, with weak flame–acoustic coupling and limited satisfaction of the Rayleigh criterion. In contrast, the non-aligned configuration exhibits overlapping unstable regions and strong modal interactions. Overall, nozzle misalignment significantly alters phase-dependent coupling, making the system highly susceptible to thermoacoustic instability even at a constant interaction index.

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Recurring phase transition in a self-organised turbulent reacting flow system

Athira P. Gokulnath[1,2], Shruti Tandon[1,2], Rohit Radhakrishnan[1,2], and Sujith R. I.[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600036, India

Thermoacoustic instability is a self-organised state characterised by large amplitude acoustic oscillations that are catastrophic in a turbulent combustion system[cite: 119]. To understand the mechanism of self-organisation, we study the growth of thermoacoustic power sources[cite: 120]. Thermoacoustic power sources feed energy into the system, and the organisation of thermoacoustic power sources enhance spatial order[cite: 121]. We show that the dual-phase evolution is the mechanism of self-organisation in the turbulent reacting flow system during the occurrence of thermoacoustic instability[cite: 122].

Phase transitions provide a theoretical framework to understand the emergence of collective behaviour in complex systems[cite: 153]. The thermoacoustic system is a complex system with multiple interacting subsystems of acoustics, reacting and flow field[cite: 154]. The spatial pattern of thermoacoustic power sources alternates between a local phase (low connectivity), Fig. 1 (c-i), and a global phase (high connectivity), Fig. 1 (c-ii)[cite: 155].

The local phase is characterised by locally connected thermoacoustic power sources, whereas the global phase arises from the merging of multiple such locally connected regions to form a spatially extensive, coherent source[cite: 156]. We observe that the transition from the local to the global phase occurs twice during an acoustic cycle[cite: 157]. Thus, we observe a recurring phase transition from local phase to global phase during the state of thermoacoustic instability[cite: 158]. A recurring phase transition is known as a dual phase evolution[cite: 159]. Furthermore, we examine phase-averaged statistics with respect to the phases of the acoustic pressure, and characterise both inter-cycle and intra-cycle variations in the phase transition arising from flow dynamics[cite: 160].

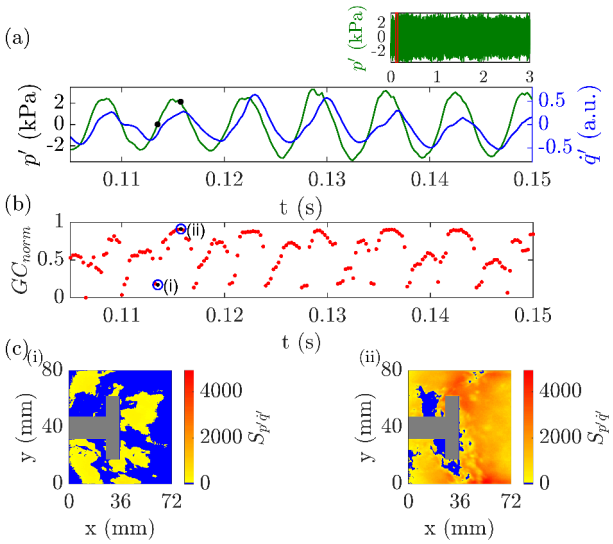

Figure 1: (a) The temporal acoustic oscillation (primary ordinate) and the global heat release rate fluctuations (secondary ordinate) during the state of Thermoacoustic instability[cite: 148]. (b) The growth of the size of the giant component of thermoacoustic power sources alternates between local phase (b-i) and global phase (b-ii)[cite: 149]. (c-i) Spatial pattern (node strength) of the thermoacoustic power sources at the local phase, (c-ii) spatial pattern (node strength) of the thermoacoustic power sources at the global phase[cite: 150]. The grey region denotes the bluff body for flame stabilisation[cite: 151]. The colorbar from yellow to red represents the node strength of thermoacoustic power sources, and the blue region represents the thermoacoustic power sinks[cite: 152].

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Mode Extraction and Analysis of Flow Structures in Corrugated Capillaries

Aaryan Dev[1], Riddhika Mahalanabis[2], Balakrishnan Ashok[2]

[1] Department of Computer Science and Engineering, International Institute of Information Technology Bangalore (IIIT-B)
[2]Complex Systems & Soft Matter Physics Lab, Centre for Applied Sciences, International Institute of Information Technology Bangalore (IIIT-B), 26/C, Electronics City Phase-1, Hosur Road, Bangalore 560100, India.

Understanding the dynamics of fluid interfaces requires careful interpretation of nonlinear governing equations. In this work, we analyze the spectral evolution of a capillary flow system by combining direct equation-based reasoning with data-driven modal analysis.

The system under consideration here is flow through a corrugated capillary with the following governing equation :

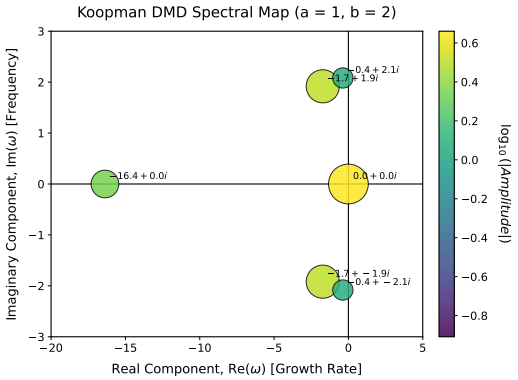
$$\alpha - \dot{h}^2 - h\ddot{h} - h\dot{h} - \beta h - fh\dot{h}^2 = 0 \qquad (1)$$

where $\alpha = \frac{r_0 \rho \sigma \cos\theta}{128\eta^2}$ and $\beta = \frac{g r_0^3 \rho^2}{128\eta^2}$. The system exhibits oscillatory behavior arising from the competition between surface-tension-driven viscous dynamics (α) and gravitational loading (β), besides a friction component (f) due to rough walls [1].

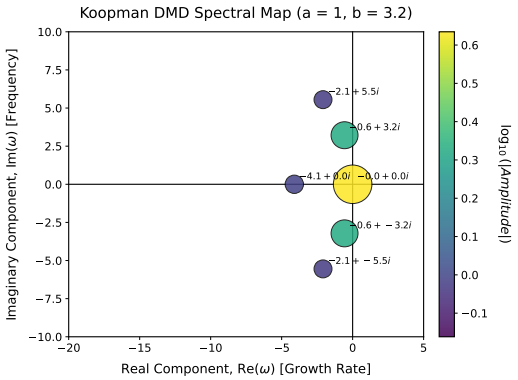
Numerical trajectories generated from this equation are analyzed via Hankel Dynamic Mode Decomposition (H-DMD) [2, 3] to extract dominant frequencies and modal amplitudes. This approach complements analytical reasoning by revealing how the modes corresponding to the system reorganize as the system parameters vary.

From our analysis [4] we observe the following key nonlinear structures. First, modal frequency follows a nonlinear decrease with increasing α. Second, increasing β produces a mode-overtaking transition in which the fundamental mode and first harmonic exchange spectral ordering. This behavior is illustrated in Fig. 1, where the relative placement of spectral branches shifts as gravitational loading (β) increases. We further analyze the physical mechanisms governing these transitions and outline how the resulting modal structure may inform control and design principles in natural and biomimetic fluid transport systems.

Together, these observations demonstrate how data-driven modal analysis can complement equation-level reasoning, offering a broader understanding of the emergent behavior of nonlinear capillary flow.



(a) Before overtaking ($\alpha = 1, \beta = 2$)



(b) After overtaking ($\alpha = 1, \beta = 3.2$)

Figure 1: DMD spectral maps illustrating mode-overtaking transition as β increases. The mode with initially smaller frequency, increases in frequency and decreases in amplitude

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Combined Effects of Stochasticity and Skop-Griffin Parameter in Dictating the Nonlinear Dynamics of a VIV System

Abhijith Arun[1], M. S Aswathy [1]

[1]Indian Institue of Space Science and Technology,Thiruvananthapuram, India

This study expands understanding of vortex-induced vibration (VIV) in circular cylinders by investigating the combined impact of random noise and Skop-Griffin parameter SG in dictating the nonlinear dynamics of an oscillating structure [2]

When a cylinder is placed in fluid flow, vortices are shed from either side of the cylinder. At a certain range of velocities, the Strouhal frequency and the natural frequency of the cylinder get closer; the two frequencies synchronises, resulting in large-amplitude vibrations called 'vortex-induced vibrations'. It is a major engineering concern for bridge cables, heat exchangers, and power lines. This regime of large amplitude oscillations is called lock in [3]

In real-life situations, though, we encounter stochastic fluctuations or 'noise' due to inherent parametric uncertainties, environmental disturbances, etc. Noise is detrimental in determining the system dynamics as it can trigger or shift instability regions and produce new dynamic states in the system [4].

Owing to the above, we study the stochastic dynamics of the (VIV) system, here we use a well-known coupled nonlinear fluid-structure interaction model by [2] where the cylinder is modelled as a classic spring-mass damper system and the fluid flow is modelled by a Van der Pol equation. In this study, we primarily explore the combined effects of both noise and a varying Skop-Griffin parameter, which is a dimensionless parameter that is a function of the mass ratio, damping ratio and Strouhal number[1].

In comparison to previous studies [3] where the dynamics of the VIV system exhibited new qualitative and quantitative behaviours under stochasticity, here one can observe a new set of temporal and frequency behaviours emerging as the mass and damping ratios are varied. During the study, we seek to identify if the existing precursor markers to instability (called 'lock-in') will get suppressed with the changes in mass ratio and damping parameters alongside noise. The dynamics of the oscillating cylinder is quantified using Poincaré maps, recurrence measures, etc.

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Explosive Synchronization in Networks of Type-I Neurons

Akshay S Harish[1], Gaurav Dar[1]

[1]BITS-Pilani, K K Birla Goa Campus, Goa, India

Explosive or abrupt transitions to synchronization have implications for several brain processes, such as epileptic seizure and switching between consciousness states. Such transitions have been studied extensively in the abstract Kuramoto oscillator networks[1]. Previously reported explosive synchronization (ES) in neuronal networks is model-dependent and lacks the generality to extend to other neuron models. Our work bridges this gap by demonstrating ES in a class of neurons. We achieve this by establishing ES in the normal form of weakly heterogeneous Type-I neurons—the QIF model and further affirming it in a Biophysical model exhibiting Type-I behavior—the Morris-Lecar model. The neurons are coupled through electrical synapses and are placed on scale-free (SF) and star networks with complete and partial degree-frequency correlations.

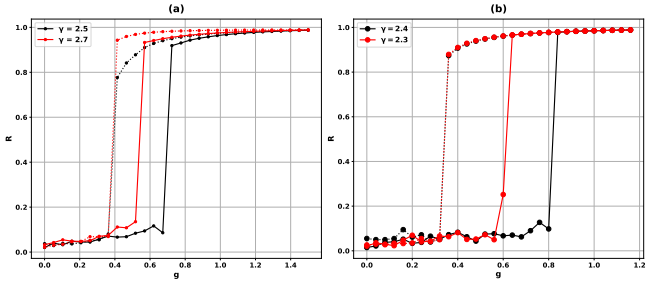

Figure 1: A sharp transition to synchronization is seen for scale-free networks of 1000 neurons with complete degree-frequency correlation for different γ values. (a) Networks of QIF neurons. (b) Networks of Morris-Lecar neurons.

Our simulations show ES in networks of both QIF and Morris-Lecar neurons, under weak heterogeneity and weak coupling. Leveraging the mapping between Type-I neurons and the Kuramoto model[2], we realize theoretical predictions of ES for different conditions on neuronal networks. As shown in Figure 2, we can realize various scenarios that are known to induce ES in the Kuramoto model on these networks of Type-I neurons.

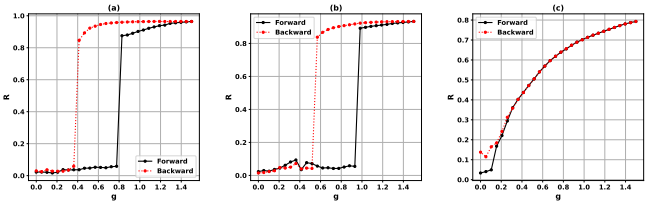

Figure 2: 1000 QIF neurons on an SF network with varying degree-frequency correlations. (a) Complete degree-frequency correlation. (b) Only the top 10% of neurons with the highest degrees have degree-frequency correlation. (c) No degree-frequency correlation.

Further, we numerically validated the mapping between the star networks of degree-frequency correlated QIF neurons and the corresponding reduced-Kuramoto model. The mean-field theory predicted critical coupling for a smaller star network, and the numerical simulation results show good quantitative agreement. Thus, this work establishes a set of conditions that allows ES to arise in weakly heterogeneous Type-I neurons near the SNIC bifurcation. The generality of these results across a class of neurons, together with their origin in the Kuramoto framework, takes us a step closer to understanding abrupt transitions in the brain.

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Strategies, Dynamics, Energy Landscapes: A Statistical Physics Framework for Analyzing Competition & Cooperation

Akshay Sanjeev K.[1,2], Shakti N. Menon[1], Sitabhra Sinha[1,2]

[1]The Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai 600113, India
[2]Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, India

Strategic competition between agents, that can occur in biological, economic or social settings, can be quantitatively understood using the framework of game theory. The dominant paradigm for solving such games is that of Nash equilibria. In contrast, the co-action principle shows that under conditions of symmetry, agents necessarily converge to the same strategy that maximizes their payoff. Surprisingly, the latter solutions are much more likely to yield cooperative behavior for various well known N-person non-cooperative games. This raises the question as to whether there is a general class of solution frameworks of which the two described above are special cases. To this end, we derive from first principles an energy landscape formalism that has an exact correspondence to the strategy space of the games. By defining a dynamical system on the strategy space, we derive the global potential functions for both symmetric and asymmetric game configurations. For the Nash framework, the potential function is shown to take a form analogous to a spin Hamiltonian. We extend the framework to asymmetric games, by introducing off-diagonal asymmetry through "shift" and "shrink" configurations. We demonstrate that while a scalar potential exists for the "shrink" type of asymmetry, the "shift" asymmetry results in a non-conservative vector field for marginal payoffs, precluding a standard potential representation in this case. Our work points towards a generalization of the theory of games that brings together concepts of dynamical systems and statistical physics.

Complexity Analysis of a Fractional-Order Murali-Lakshmanan-Chua (MLC) Circuit

Arif T. A.[1], Nadhiya K. V.[1], Ishaq Ahamed A.[2]

[1]Department of Physics, Ansar Women's College, Perumpilavu, Thrissur, India
[2]Department of Physics, Jamal Mohamed College (Autonomous),
Affiliated to Bharathidasan University, Tiruchirappalli, India

This paper investigates the complexity in the dynamical behaviour of a fractional-order Murali-Lakshmanan-Chua (MLC) circuit [1]. This system is converted into a discrete map using Adomian Decomposition Method (ADM) [2] and solved numerically [3]. The Lyapunov Characteristic Exponents (LCEs) are computed to identify the different dynamical behaviours in the system. These are observed by plotting the bifurcation diagrams, phase portraits, and spectral entropy graphs.

A systematic exploration of the influence of the fractional order parameter q on the system dynamics, reveals the emergence of rich nonlinear phenomena, such as periodic oscillations, chaotic attractors etc. In particular, the system transits from regular dynamics to chaotic behavior as the fractional order q decreases [4].Further spectral entropy graph and complexity analysis of the system is carried out. This analysis also demonstrates the increase in complexity as the fractional order parameter is lowered.

Keywords: Fractional-order calculus; Adomian decomposition method; MLC circuit; Chaos;Phase Portrait; Spectral entropy; Lyapunov exponents; Bifurcation analysis.

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Nonlinear public goods games through fitness interdependence

Amit Basak[1], Christian Hilbe[2], Supratim Sengupta[1]

[1]Indian Institute of Science Education and Research Kolkata, Mohanpur Campus, India
[2]Interdisciplinary Transformation University, Austria

The public goods game (PGG) is a foundational model in evolutionary game theory to study the emergence and stability of cooperation during a social dilemma faced by members of a group. In such models, individuals choose whether to contribute a fixed amount c to a common pool (cooperate) or not (defect). The total contribution is multiplied by a *fixed* multiplication factor called the productivity r and then evenly redistributed among all group members, regardless of their contribution. Since the benefit is shared while the cost is borne individually, defection yields a higher individual payoff, making cooperation evolutionarily unstable in well-mixed populations when the productivity is smaller than the group size. In this public goods game, the benefit of contribution linearly increases with the number of cooperators; as a consequence, this scenario is often referred to as the linear PGG. There has been a predominant focus in both evolutionary theory and behavioral experiments on the linear PGGs, particularly in settings where interactions are constrained to a single group. In nature, however, linear PGGs are rare [1], and often, the welfare of one group depends on that of other groups [2]. Starting from microbial communities to human societies, multiple groups are often found to share costly public goods which they produce, each of which helps sustain the other, and can coexist stably[3]. Here, we study a model of an interdependent public goods game in which each group shares a fraction of its costly public goods with the other group. The productivity (marginal per capita return) of the public goods in each group depends not only on contributions from its own group but also on those from the other group, resulting in a nonlinear PGG within each group. The interdependence between groups through productivity and resource sharing can break the curse of defection dominance found in the linear PGG of an isolated group and gives rise to richer dynamical outcomes in evolutionary settings (Fig. 1). We find that resource sharing can be critical for sustaining cooperation within groups; however, excessive sharing can weaken cooperation and even drive both groups toward defection. Analytically, we identify a critical threshold of resource sharing beyond which defection dominates via a nonlinear phase transition. We also propose a general framework of fitness interdependence to study the evolutionary dynamics of cooperation across groups. Our results shed light on how different forms of interdependence can give rise to cooperation and competition among groups.

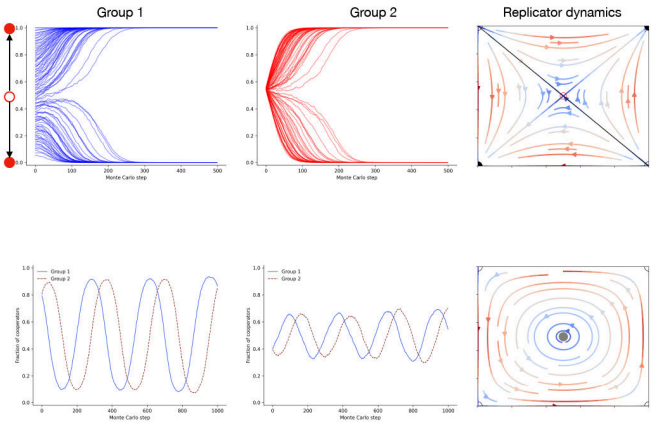

Figure 1: Evolutionary dynamics of interdependent public goods games across groups. The top panel shows the outcome of a Monte-Carlo simulation and trajectories of the solution of replicator dynamics when two groups are positively interdependent on each other. The lower panel shows the outcome when groups have opposite effect on each other's productivity.

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One-Dimensional Reduction of Dynamical Systems on Networks with Higher-Order Interactions

Amitosh Tiwari[1] , **Chittaranjan Hens**[2,3], **Prosenjit Kundu**[1]

[1]CSys Lab, Dhirubhai Ambani University, Gandhinagar, Gujarat 382007, India
[2]Center for Computational Natural Sciences and Bioinformatics, International Institute of Information Technology Hyderabad, Gachibowli, Hyderabad 500032, Telangana, India
[3] Biomedical Research Center, International Institute of Information Technology, Gachibowli, Hyderabad-500032, India

Low-dimensional reduction is a powerful framework for understanding collective dynamics in large networks, but existing approaches are largely restricted to pairwise interactions. We develop a one-dimensional effective-state reduction for dynamical systems with purely higher-order interactions on simplicial complexes.

We consider a system of N nodes whose interactions occur through triangle structures, represented by simplicial complexes. The state of node i evolves according to

$$\dot{x_i} = F(x_i) + D_\Delta \sum_{j=1}^{N}\sum_{l=1}^{N} T_{ijl} H(x_i, x_j, x_l), \quad i = 1, \ldots, N \qquad (1)$$

where $x_i \in \mathbb{R}$ denotes the dynamical state of node $i, F(x_i)$ describes its intrinsic dynamics, and $H(x_i, x_j, x_l)$ represents the combined influence of nodes j and l on node i. The tensor $T_{ijl} \in 0, 1$ is the unweighted and undirected third-order interaction tensor, where $T_{ijl} = 1$indicates a higher-order interaction among nodes i, j, and l. The parameter D_Δ controls the strength of the higher-order coupling.

The method is built around an effective higherorder coupling strength induced by triangular motifs, yielding a compact description that combines network structure and collective dynamics. We derive the reduction through explicit approximations and identify the conditions under which it remains reliable. Across double-well, gene-regulatory, and SIS epidemic models on synthetic and real networks, the reduced dynamics accurately captures steady states and transitions when node states remain sufficiently homogeneous.

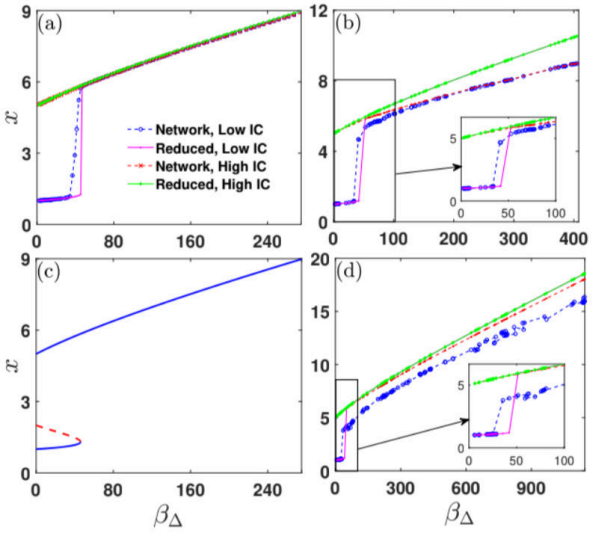

Figure 1: **Double-well system with higher-order interactions.** Steady-state value x as a function of the effective higher-order interaction strength β_Δ. Panels (a) and (b) compare the full-network simulations with the one-dimensional reduction for Erőds–Rényi and Barabási–Albert networks, with $p = 0.1$ and $m = 12$, respectively, where m is the number of edges attached by each new node during growth. Panel (c) shows the bifurcation diagram of the reduced system, including the stable and unstable branches. Panel (d) shows the corresponding comparison for the GR-QC collaboration network. The reduction captures the main branch structure and the transition from the low state to the high state, with stronger agreement for the synthetic networks than for the real-network low-initial-condition branch.

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ENSO Prediction: Complex Dynamics of El Nino and La Nina Modelling

Angana Das Mahapatra[1,2 a], **K V Ramesh** [1,2],

[1]CSIR-National Institute of Interdisciplinary Science and Technology
[2]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

The El Nino Southern Oscillation (ENSO) is a dominant mode of interannual climate variability, which influences global weather patterns, ecosystems, and socio-economic structures. Accurate prediction of ENSO events remains a central challenge in climate science due to its complex coupled ocean-atmosphere dynamics and inherent nonlinearities. Mathematical climate models, ranging from conceptual dynamical models, coupled general circulation models (CGCMs) to hybrid physics-informed and machine learning frameworks, are all essential tools for understanding ENSO dynamics and improving forecast skill. Among them, Recharge-Discharge oscillator model represents the main idea that ENSO cycles are driven by changes in the heat stored in the equatorial Pacific. Changing from an El Niño to La Niña event can be described by a pair of linked equations for heat content and SST, forming a mathematical oscillator that naturally swings between warm and cool phases.

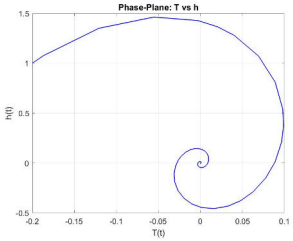

Figure 1: Phase space of Delayed RDO system

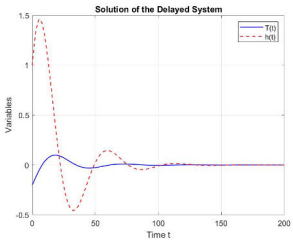

Figure 2: Equilibrium point reaching through delayed RDO

$$\frac{dT}{dt} = cT + Dh - \epsilon T^3, \frac{dh}{dt} = -FT - Rh \quad (1)$$

The variable $T(t)$ represents the sea surface temperature (SST) anomaly, $h(t)$ denotes the thermocline depth anomaly, and c, D, ϵ, F,R are the respective parameters representing eastern Pacific Ocean basin(Nino 3) adjustment. In this model, the detailed wave propagation process is not emphasized. Equatorial wave dynamics are collectively viewed as an ocean adjustment process to redistribute mass and heat under changing wind stress forcing. However, recent research indicates that this model can be extended to account for the diverse spatial patterns of ENSO variability, with anomaly centers in either the central or eastern Pacific. In the delayed oscillator theory, the negative feedback by free Rossby waves reflects from the western boundary, returning as Kelvin waves to reverse the anomalies in the eastern Pacific coupling region.

$$\frac{dT}{dt} = cT + \alpha T(t-\tau) - \epsilon T^3 \quad (2)$$

But phase transitions are not systematic due to random Westerly Wind Bursts(WWBs) and Kelvin waves are influenced by WWBs. In RDO model of ENSO all delay parameters are previously set to zero without considering the need the explicit role of wave propagation. Combining both of the system and incorporating values of the parameter wrt recent observational data, these are the results that follow from Fig 1 and 2, which can be considerd for predicting further ENSO events.

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Recurrence Network Analysis Uncovering Biomarkers of Depression from Nonlinear Dynamics underlying EEG Signals

Angitha Jeesis C[1], Jasleen Gund[2], Divya Sindhu Lekha[1]

[1]IIIT Kottayam, Kerala, India
[2]Amity Institute of Biotechnology, Amity University, Noida, India

Major Depressive Disorder (MDD) is one of the most prevalent and severe mental health condition, affecting millions of individuals worldwide and often leading to significant cognitive and emotional dysfunction. MDD is characterized by persistent low mood, loss of interest or pleasure, and impaired cognitive and physical functioning. Our objective is to apply advanced complexity and recurrence network analysis approaches to investigate underlying changes in the functional brain connectivity using electroencephalographic (EEG) signals.

We have used the multi-modal open dataset for mental-disorder analysis (MODMA), consisting of 128-channel resting-state EEG recordings of individuals with MDD and that of healthy controls. We have particularly focussed on channels in the frontal brain region as it is known to play a crucial role in the emotional and cognitive processing. After the pre-processing, power spectral density (PSD) and Lempel-Ziv (LZ) complexity analysis were applied to distinguish MDD subjects from healthy controls. We performed t-tests to identify significant channels. We then constructed recurrence networks to capture the nonlinear temporal dynamics of EEG activity in these significant frontal channels. Then, we computed various network measures, including Recurrence Quantification Analysis (RQA), recurrence rate (RR), determinism (DET) and laminarity (LAM) to characterize the resulting recurrence network. Further, we performed functional cartography of nodes based on modularity to quantify network hubs.

The results revealed frontal asymmetry with several frontal channels exhibiting significant variations in oscillatory power and signal complexity in MDD. The recurrence networks represent the complex interrelationships among recurring patterns of EEG brain activity over time. We observed that functional cartography applied for hub classification in the constructed recurrence networks provides a powerful framework for quantitative analysis and unveiling network based signatures underlying the nonlinear dynamics of EEG signals.

The results revealed frontal asymmetry, with several frontal channels exhibiting significant variations in oscillatory power and signal complexity in MDD. The recurrence networks captured complex interrelationships among recurring patterns of EEG activity over time. Functional cartography applied to the constructed recurrence networks provided a useful framework for hub classification and for uncovering network-based signatures underlying the nonlinear dynamics of EEG signals.

The identification of such EEG-based network markers could facilitate early detection and prediction of MDD severity.

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Learning in a population of excitatory and inhibitory neurons

Anuran Pal[1,2], **Sitabhra Sinha**[1,2]

[1]The Institute of Mathematical Sciences (IMSc), Chennai, 600113, India
[2]Homi Bhabha National Institute, Anushakti Nagar, Mumbai, 400094, India

The key features of the brain are its ability to process information and to learn from the experience. The unit of brain, a neuron, receives signals through its dendrites, reevaluates its state, and sends the information of its current state through its axon. The axon of a neuron branches out and connects to the dendrites of other neurons by forming chemical synapses, which transmit the information of the presynaptic neuron's state to the postsynaptic neuron. These synapses form the connection topology of the neurons, making synaptic plasticity the basis of learning in the brain. The most successful modelling paradigm that captures this form of collective learning by networks are neural network models, where the neurons are approximated as binary switches. Several methods exist that enable learning of the connections between these binary elements, but the most biologically plausible mechanism is learning via association. Colloquially recognized as "neurons that fire together, wire together", this associative form of learning was first illustrated successfully in Hopfield's model of neural networks, where the connection between any two switches is the pairwise correlation between those two switches over the set of patterns being learnt: $W_{ij} = \sum_{\alpha=1}^{m} \xi_i^\alpha \xi_j^\alpha$, where ξ_i^α corresponds to the state of the i^{th} neuron in the α^{th} pattern. This method of learning produces symmetric interaction matrix, which can then be used in the spin Hamiltonian, making pattern recognition synonymous with energy minimization. However, the brain is inherently asymmetric because of the categorization of every neuron into either of the two distinct classes: excitatory or inhibitory, defined by the nature of a neuron's axonal synaptic vesicles, which translates to a switch having only $+/-$ outgoing links, not both. Recognized as Dale's principle, this categorization fundamentally breaks the interaction symmetry, prohibiting an energetic description of the system, but enabling dynamic steady state behaviour, like oscillation and chaos in the system of switches. Exploiting the similarity between the continuous-time Hopfield model and Wilson Cowan's phenomenological model, we try to accommodate Dale's principle by considering excitatory-inhibitory couple as a single neuron motif over which the network engages in learning by modifying intermotif connections.

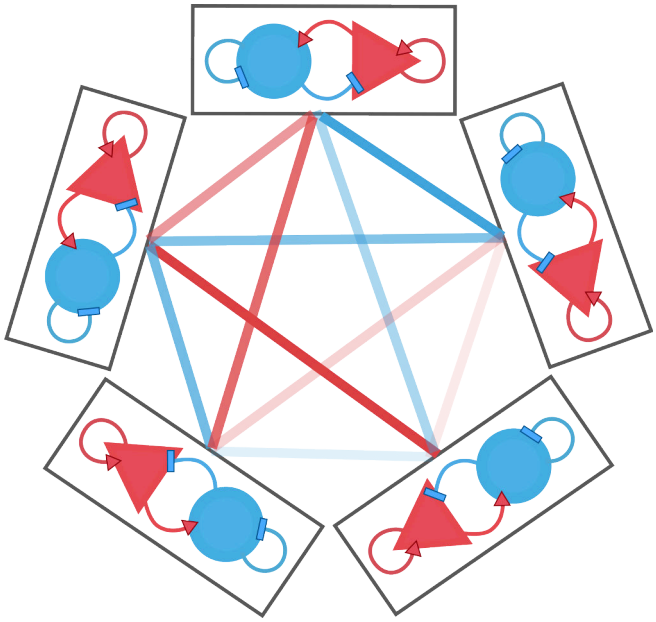

Figure 1: Learnable network of excitatory-inhibitory motifs

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Tragedy of the Commons through Regime Shifts in Eco-Evolutionary Game Dynamics of Renewable Resources with Allee Effects

Arthana M[1], Biswambhar Rakshit[1]

[1]Department of Mathematics, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham , Coimbatore, 641112, Tamilnadu, India

Unsustainable exploitation of environmental resources can destabilize ecosystems, increasing the risk of sudden collapse of the common resource pools through regime shifts. This sudden collapse of common resources also know as the tragedy of the commons (TOC), is a fundamental problem in game theory.

We adopt an eco-evolutionary game-theoretic framework to study the dynamics of a coupled human–environment system with a renewable resource [1, 2]. The resource dynamics follows logistic growth with an Allee effect and is subject to a Holling type-I functional response. Incorporating population behaviors, individuals are assumed to adopt one of the two strategies, low-effort or high-effort. We model the payoff matrix as an environment-dependent interpolation between two extremes $n = 0$ (depleted state) and $n = 1$ (replete state) determining the relative contribution of each. In particular, we focus on how variations in harvesting effort of defectors lead to the emergence of the tragedy of the commons through regime shifts.

The coupled human-environment system are given by

$$\left.\begin{aligned} \frac{dx}{dt} &= x(1-x)(\pi_L(x,n) - \pi_H(x,n)) \\ \frac{dn}{dt} &= rn(1-\tfrac{sn}{K})(\tfrac{sn}{A}-1) - \\ &\quad q(e_L x + e_H(1-x))n. \end{aligned}\right\} \quad (1)$$

where π_L and π_H are the average payoff of playing low or high effort strategy, respectively.

By assigning the depleted and replete state of two distinct games chosen from the Trivial, Chicken, Stag-hunt, and Prisoner's dilemma games, we obtain six game combinations for analysis. Variation in harvesting effort can drive the system towards a tragedy of common through regime shifts, revealing a rich spectrum of underlying bifurcation mechanism.

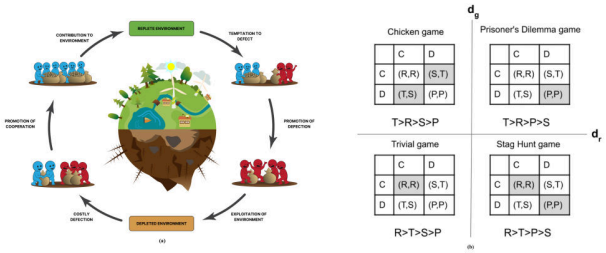

Figure 1: (a) Schematic diagram of a coupled human-environment system , (b) The categorization of four game classes on the d_r-d_g plane.

Overall, our investigation reveals complex dynamical behavior of the coupled system with presence of initial-condition-dependent TOC or TOC. Moreover, variation in the system parameters can either delay environmental collapse or accelerate its onset. Our results indicates that resource abundance depend not only on intrinsic ecological dynamics but also on emergent human behavior towards the environment. Adaptive strategies or proper incentives leads to sustainable resource stock even in presence of defectors.

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Compression spectrum framework for characterizing brain states and disorders

Aditi Kathpalia[1], Ashutosh Rathore[1], Nithin Nagaraj[2]

[1]Indian Institute of Technology Madras, Chennai, India
[2]National Institute of Advanced Studies, IISc Campus, Bengaluru, India

Power spectral analysis (PSA) and complexity estimation are standard tools for characterizing neurophysiological states, from sleep and anesthesia to disorders like epilepsy and Alzheimer's. While PSA helps to analyze the strength of frequency components present in the signal, complexity measures like Shannon Entropy and Lempel-Ziv analyze the signal's structural randomness or unpredictability. PSA typically relies on Fourier-based methods (assuming linearity and stationarity), while complexity approaches use probability distributions or compressibility for their estimation. Despite their overlapping applications, these two frameworks remain methodologically exclusive.

The authors have proposed the Compression Spectrum [1], a novel approach that leverages the Effort-To-Compress (ETC) [2] algorithm to bridge this gap. Unlike traditional power-vs-frequency spectra, the compression spectrum displays information content across different scales, providing a frequency-dependent profile of signal complexity. This method has been validated using simulated datasets, demonstrating its ability to differentiate between periodicity, chaos, and randomness, and also effectively characterizing $1/f$ noise.

In this work, we apply the compression spectrum to the Bonn University EEG dataset to distinguish between healthy, interictal (non-seizure), and ictal (seizure) recordings. This dataset comprises of 100 recordings for each case from 5 healthy and 5 epileptic subjects. Statistical analysis reveals that features such as spectral bandwidth, maximum scale, ETC iterations, and the fluctuation index of the compression spectrum are strongly statistically significantly different across these groups. Figure 1 displays the histograms of spectral bandwidth obtained for recordings from normal and epileptic subjects (not undergoing a seizure).

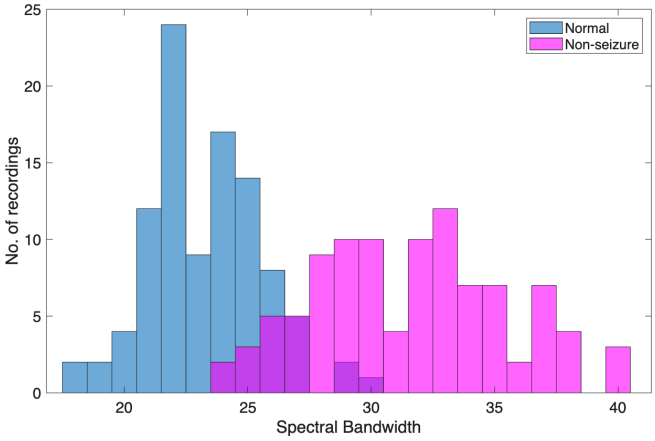

Figure 1: Histograms displaying compression spectrum bandwidth obtained for normal and epileptic patients (in non-seizure condition).

Additionally, we explore the use of this method to compare between awake, anaesthesia and awake state in monkeys. For this, we use open access Neurotycho database of ECoG recordings obtained from four different monkeys. Our results suggest that the compression spectrum offers a robust, unified framework for quantifying the dynamic complexity of brain states.

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Metallic Hydrogen: The possible reason of the strong magnetic field of Jupiter

Ashutosh Satapathy

North-Eastern Hill University, Shillong, India

Hydrogen, the most abundant element in the whole universe, is most probably the simplest atom ever to exist. But under extreme pressure and at extreme low temperature, it has the ability to transition into a metallic state having properties fundamentally different from the molecular hydrogen as well as the atomic hydrogen. In 1935, E. Wigner and H.B. Huntington was the first who predicted that Hydrogen could transform into metallic solid exhibiting similar electrical conductivity as of conventional metals [1]. More than eight decades later, scientists reported the evidence of formation of it in lab conditions with a pressure approaching to 495 GPa and temperature around 5.5 Kelvin having a high optical reflectance of around 0.91 and signature of traditional metals. They have also predicted that the Solid Metallic Hydrogen (SMH) may have a metastable state at room temperature which may remain solid at room temperature even after the pressure is removed [2].

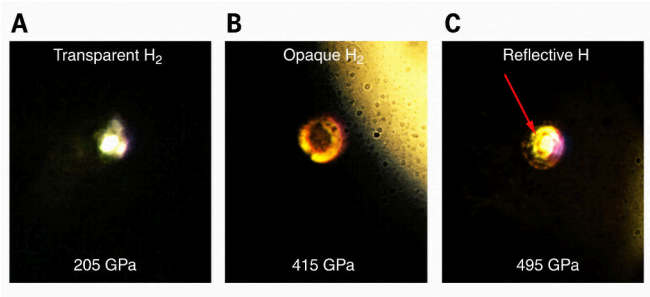

Figure 1: This image is taken from the second reference mentioned in the reference section.

In addition, several studies have proposed that it could display the characteristics of a super conductor [3] [4], making it a subject of interest for producing high magnetic fields [5] which can be used in MRIs, particle accelerators, fusion reactors, quantum computing and many more sectors. Beyond the laboratory, the SMH also plays a vital role in planetary sciences. Spectroscopic signature received from Jupiter indicates that Jupiter is predominantly consisting of Hydrogen and Helium [6]. The data received from Juno suggests that the core of Jupiter may not have a small solid core consisting of heavy atoms. Under the extreme pressures within the planet, metallic hydrogen is believed to occupy a significant fraction of the whole interior of Jupiter and is considered the reason for its powerful planetary dynamo and magnetic field generation [7].

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Parasite enrichment drives inequality before collapse in a model of evolving networks

Atiyab Zafar[1], Sanjay Jain[1,2]

[1] Department of Physics and Astrophysics, University of Delhi, Delhi, India
[2] Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, New Mexico 87501, USA

Many complex systems, including stock markets and civilizations, can undergo collapse, and understanding why this happens is important for forecasting and response planning. Here, we study collapses in a mathematical model [1] of an evolving directed network with $(S \gg 1)$ nodes. In the model, the eigenvector centrality (X_i) of node i is taken as the node's "strength." The network evolves one node at a time by replacing the weakest node (the node with the smallest (X_i)) with a new node that connects randomly to the existing network with connection probability (p). As the network evolves, the model shows spontaneous growth, stasis, and collapse in the number of nodes with non-zero strength, where a collapse corresponds to a sudden drop in this number. Previous studies have identified proximate causes of collapse in this model, [2, 3, 4] but the long-term dynamics that makes the network fragile and susceptible to collapse remains unclear. To probe this long-term approach to collapse, we compute the Gini coefficient, a standard measure of inequality, for the distribution of node strengths (X_i). We find that inequality rises on average as the network approaches collapse. We also find that the strength of peripheral parasitic nodes increases as collapse is approached; these nodes become richer at the expense of the core. Peripheral nodes are "parasitic" in the sense that they benefit from the core that sustains them but do not provide feedback that supports the core. This shift of strength away from the core makes the network more fragile and more prone to collapse. These lessons from the model and the above mentioned early warning signals of collapse may be relevant for other complex adaptive systems.

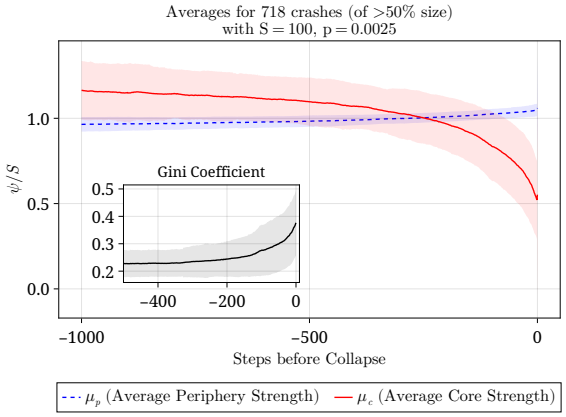

Figure 1: Periphery getting richer and rising inequality before collapse. The x-axis shows time in graph updates, with collapse at zero. Quantities are averaged over 718 runs ($S = 100$, $p = 0.0025$), each ending in a collapse. The red solid (blue dashed) curve shows the mean μ_c (μ_p), the average strength of core (periphery) nodes, across all runs. The blue dashed curve crossing and exceeding the red solid curve indicates parasites getting richer before collapse. The inset shows the Gini coefficient averaged over the same runs, representing rising inequality. Shaded bands (pink, blue, grey) denote one standard deviation of μ_c, μ_p, and the Gini coefficient respectively.

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On Branching Patterns in Lightning: A Dynamical Perspective on Ground Strikes

Awantika Mishra

Independent, Mau (U.P), India

Lightning is a fascinating phenomenon at once familiar and striking, like a spark across the sky, unfolding in branching patterns reminiscent of trees. Despite this visual resemblance, lightning is deeply consequential, responsible for significant loss of life during the monsoon season. In October 2025, for instance, 25 people died within two days in my state alone. This motivates a simple but unresolved question: what determines whether a lightning discharge remains suspended within the cloud or connects to the ground?

In this work, I approach this question through the lens of bifurcation dynamics. Lightning channels may be viewed as evolving structures shaped by local interactions and global field conditions, where multiple potential paths compete before a single trajectory is realized. Using simplified growth models inspired by dielectric breakdown processes, I examine how variations in environmental parameters such as field gradients and stochastic perturbations affect the morphology of branching patterns.

Of particular interest is the transition from exploratory, diffuse branching to directed propagation toward the ground. I propose that this transition may be understood as a bifurcation-like behaviour, where small changes in system conditions lead to qualitatively different outcomes. By situating lightning within a broader class of branching systems, this study aims to contribute to a more intuitive and dynamic understanding of ground strike formation, with potential implications for improving early warning strategies during the monsoon season.

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Figure 1: Representative branching pattern in lightning discharge.

Bifurcation Analysis of Nonlinear Dynamics in Heterogeneous Catalysis

Avigyan Saha[1],Suneet Singh[1]

[1]Indian Institute of Technology Bombay, Mumbai, India

Bifurcation analysis is an indispensable tool for elucidating the intricate dynamics governing chemical reaction systems. Given the inherent nonlinearity of most chemical processes, analytical solutions to the governing differential equations remain elusive. Consequently, computational and numerical approaches serve as cornerstones in understanding and predicting reaction behavior. Heterogeneous catalytic reactions exhibit an astonishingly rich array of dynamical behaviors, including multistability, oscillatory regimes, and chaos, necessitating an in-depth comprehension of the underlying physical and chemical interactions. To rigorously investigate these complex dynamics, a reduced-order mathematical model is formulated, comprising a system of nonlinear ordinary differential equations. We conduct a comprehensive investigation of various bifurcation phenomena by employing phase plane analysis and nullcline plotting in codimension-one framework using MATLAB. Additionally, we rigorously establish the existence and stability of equilibrium points, providing deeper insights into the system's dynamical behavior. Numerical simulations are used to demonstrate different types of oscillations and chaos in the kinetic model of heterogeneous catalytic reactions.

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Metastable Network Reconfiguration in EEG as a Dynamical Signature of Working Memory States

Sivarenjani Balasubramanian[1], **Ramesh Naidu Annavarappu**[1]

[1]Pondicherry University, Puducherry, India

Working memory (WM) is a core cognitive function that depends on dynamic interactions among large-scale brain networks to transiently store and manipulate information. Rapid transitions between network configurations are therefore central to understanding complex neural dynamics during WM. Electroencephalography (EEG) offers a non-invasive means of capturing fast neural activity, allowing the characterisation of functional integration across cortical regions during WM processes.

In this study, EEG data were recorded while participants performed a modified Sternberg item recognition task. The continuous data were segmented into distinct WM stages: pre-encoding, encoding, maintenance, and retrieval, and each stage was analysed using functional connectivity and graph-theoretic measures. Functional connectivity was quantified with the weighted Phase Lag Index (wPLI) in the theta, alpha, beta, and gamma frequency bands, yielding weighted graphs $G(V, E)$, with nodes corresponding to electrodes and edge weights corresponding to wPLI values. The wPLI was computed as

$$wPLI = \frac{|\langle |\Delta\phi(t)| \cdot \mathrm{sign}(\Delta\phi(t))\rangle|}{\langle |\Delta\phi(t)|\rangle} \quad (1)$$

To characterize local network integration, nodal strength was defined for each node i as

$$s_i = \sum_j A_{ij}, \quad (2)$$

where A_{ij} denotes the weight of the edge between nodes i and j. Nodal strength thus provides a summary of how strongly each electrode is functionally coupled to the rest of the network.

The analysis revealed systematic variations in nodal strength across WM stages, indicating dynamic reconfiguration of brain networks as task demands evolved. Stage-dependent changes in nodal strength reflect the redistribution of connectivity to support different cognitive operations, with higher values indicating greater network integration and coordination. These variations imply that the brain transitions through distinct network states during WM, balancing global integration with localised specialisation to support efficient information processing and maintenance. Frequency-specific effects further shaped this reconfiguration, with beta-band activity contributing prominently to enhanced network integration and alpha-band activity supporting adaptive adjustments under increasing cognitive load.

Overall, the results indicate that WM engages dynamic transitions between distinct network states, characterized by stage- and frequency-dependent shifts in global integration. From a complex systems perspective, this pattern is consistent with metastable switching between attractor-like states, enabling cognitive processing that is simultaneously flexible and stable.

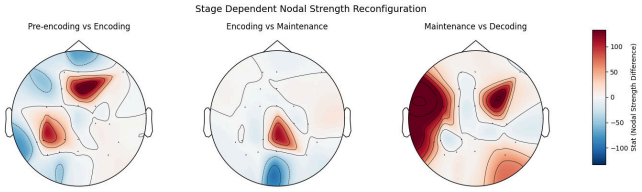

Figure 1: Dynamic Network Reconfiguration during WM tasks in Beta frequency region.

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Complex networks approach reveals monsoon extreme rainfall events propagation towards the Indian regions

Balakrishnan Sekar[1,2], Gaurav Chopra[3], Devabrat Sharma[1,2],Shruti Tandon[1,2], B. N. Goswami[4], R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology (IIT) Madras, Chennai–600036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, IIT Madras, Chennai–600036, India
[3]Department of Applied Mechanics, IIT Delhi, New Delhi–110016, India
[4]ST Radar Centre, Gauhati University, Guwahati-781014, India

In recent years, India has been experiencing an increased frequency of extreme rainfall events (EREs), leading to floods, landslides, public health emergencies, and substantial economic losses. In the Indian subcontinent, EREs mainly occur during two seasons: the Southwest monsoon (June–September) and the Northeast monsoon (October–December). Central India (CI) sees the highest EREs during the Southwest Monsoon, while Southeastern Peninsular India (SEPI) records most of its EREs in the Northeast Monsoon. To protect lives and minimize economic losses, it's crucial to understand the atmospheric connections, physical mechanisms, and variability of EREs. This study examines the propagation of EREs using the complex networks. It uses a nonlinear statistical method, event synchronization, to analyze the temporal synchronization of time series of EREs of different global locations. The topology of the complex network reveals that EREs over CI are associated with parts of Southeast Asia, the South China Sea, and the Western Pacific Ocean during the southwest monsoon. Similarly, EREs over SEPI are associated with the equatorial east Indian Ocean and Bay of Bengal during the northeast monsoon. Network divergence, a network measure, is the difference between a node's incoming and outgoing links, indicating the directionality of its interactions. It reveals propagation of EREs from the equatorial east Indian Ocean towards CI during the southwest monsoon, and towards SEPI during the northeast monsoon. The meridional wind anomaly and bandpass-filtered outgoing longwave radiation reveal the physical mechanisms behind the links and propagation. The wind anomaly strongly indicates that westward-propagating synoptic-scale low-pressure systems, such as cyclones and the Asian summer monsoon quasi-biweekly mode, an atmospheric wave, could physically connect the study regions with the maritime continent during EREs. The outgoing longwave radiation, which serves as a proxy for cloud coverage, suggests that the specific phases of the Madden–Julian Oscillation, an eastward-moving atmospheric-oceanic disturbance, likely increase the frequency of EREs over CI and SEPI.

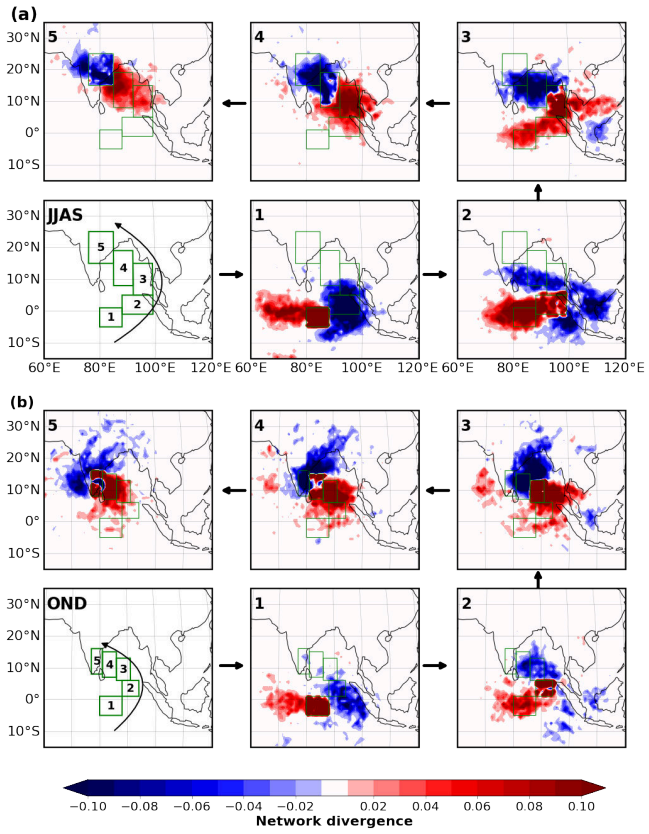

Figure 1: Network divergence of directed networks. **(a)** propagation pathway of EREs towards SEPI during the southwest monsoon (JJAS). **(b)** propagation pathway of EREs towards CI during the northeast monsoon (OND).

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Experimental investigation of shock-induced tipping in a thermoacoustic system

Bhadra Sreelatha[1,2], Rohit Radhakrishnan[1,2] and R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600 036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600 036, India

Tipping refers to the transition of a system from one dynamical state to another. Ashwin et al. [1] outlined three mechanisms for tipping: bifurcation-induced, noise-induced and rate-induced. A fourth theoretically proposed tipping mechanism, known as shock-induced tipping [2] (S-tipping), occurs when a single large disturbance triggers the system to tip. In this study, we present the first experimental demonstration of shock-induced tipping using a prototypical laminar thermoacoustic system, a horizontal Rijke tube [3].

In thermoacoustic systems, unsteady heat release rate couples with acoustic waves through positive feedback, leading to the onset of self-sustained limit cycle oscillations (LCO). The Rijke tube is a thermoacoustic system consisting of a 1 m long tube with a mean airflow and an electrically heated grid, offering a well-controlled setup for studying transitions in dynamical systems. For the range of operating conditions used in this study, the system is bistable with both quiescent and oscillatory states coexisting and exhibits a subcritical Hopf bifurcation to the state of LCO. A shock is induced by providing a sudden increase in voltage supplied to the grid to take it to a value within the bistable region. The system is seen to tip from the quiescent state into a state of LCO without the control parameter crossing the stability boundaries.

When the voltage supplied to the grid was gradually increased to a value within the bistable region, the system remained in the quiescent state as seen in Fig. 1a . However, when the same final voltage was reached by applying a sudden shock producing a change of 1.66 V within 0.3 ms, tipping to LCO was observed as seen in Fig. 1b .

To explain the underlying mechanism linking the shock in supplied voltage to the observed tipping behavior, we model the system by modifying the governing equations of the Rijke tube [3] to incorporate the heat transfer properties of the grid.

We observe that the tipping event depends on the magnitude of shock and the temperature of the grid. We show that when such a S-tipping occurs, the control parameter remains within the stability boundary, but at the same time, the system exceeds a critical threshold in the temperature of the grid (another variable of the system), which pushes the system into the basin of attraction of the state of LCO.

Our findings establish shock-induced tipping as a distinct and practically observable phenomenon, expanding the current framework of critical transitions in nonlinear systems. Understanding the mechanisms underlying shock-induced tipping is crucial for developing systems with improved safety and reliability.

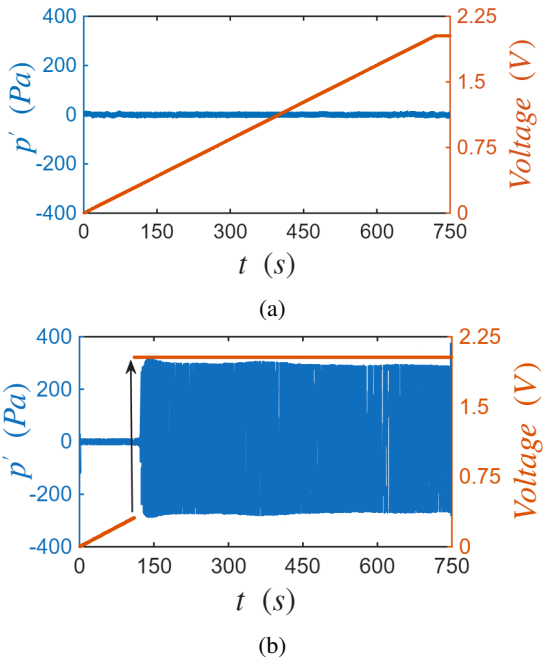

Figure 1: (a) When the voltage is increased at a constant rate, without a shock, the system remains in the quiescent state, reflected as the noise floor with a mean near zero. (b) The voltage is linearly increasing at a constant rate and then abruptly increased as shown by the arrow and subsequently held constant at that value. The shock drives the system from a quiescent state to a state of high-amplitude limit cycle oscillations.

We acknowledge the funding from IoE-IITM Research Initiative (SP/22-23/1222/CPETWOCTSHOC).

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KANS-Map: Kolmogorov-Arnold Networked S-Maps for Forecasting Non-Autonomous Dynamics

Bhavya Bansal[1], Raktim Ray[1], Partha Sharathi Dutta[1]

[1]Department of Mathematics, Indian Institute of Technology Ropar, India

Forecasting complex dynamical systems with parameters varying similar to bounded-noise remains a critical challenge in empirical dynamic modeling (EDM) [1, 2]. Classical equation-free techniques, such as standard global S-Maps, struggle with these systems because the underlying phase-space manifold continuously evolve. In this work, we propose KANS-Map (Kolmogorov-Arnold Networked S-Maps), a hybrid framework that bridges classical phase-space reconstruction with modern neural routing to handle shifting dynamical regimes.

The proposed architecture entirely avoids assuming parameter stationarity. Instead, it utilizes a Kolmogorov-Arnold Network (KAN) as a classifier. The KAN evaluates the delay-coordinate geometry of the current observed state and routes it to a specialized local S-Map "expert" representing that specific physical regime. This approach is highly advantageous over standard regularized S-Maps [3] and equation-discovery models like SINDy [4], as it allows for equation-free prediction across fluctuating physical rules without requiring explicit knowledge of the external forcing variables.

The effectiveness of the KANS-Map framework is demonstrated through its application to the chaotic Hastings–Powell model [5], where an underlying system parameter is continuously varied similar to bounded-noise where the amplitude is sampled from uniform distribution and the duration for which the amplitude remains constant is sampled from geometric distribution.

Figure 1 represents a box-plot, validating the proposed method's ability to perform better than the standard S-Maps on an average.

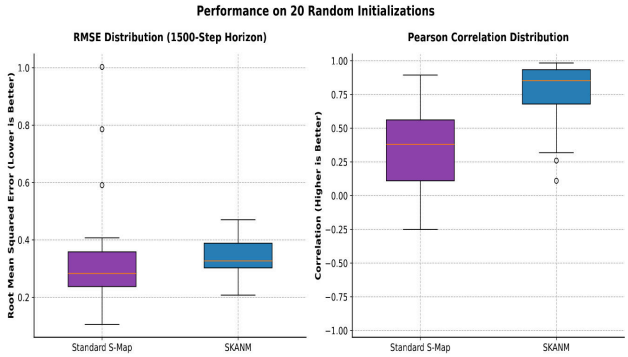

Figure 1: Box-Plot of Comparison between Standard S-Map and KANS-Map

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Characterizing Chaos in Cryptographic Hash Functions using Segmented Bit-Stream Trajectories

Bhushan M. Chinchalkar[1], Dr. Rajesh Ingle[1]

[1]Computer Science and Engineering, DES Pune University, Pune 411004, India

Implementations of chaos-based cryptographic hash functions are often constrained by "information leakage" and trajectory "cramping" due to the limits of finite-precision arithmetic. Standard evaluative metrics, such as Global Shannon Entropy, may lack the resolution required to distinguish between chaotic ergodicity and numerical noise generated by rounding errors. This research explores an analytical approach that treats high-bit-depth registers as spatio-temporal sequences of segmented bit-windows at varying resolutions, such as 2-bit, 3-bit, or 4-bit segments.

By mapping these discrete segments onto a sequential timeline across the algorithm's iteration space, a "bit-stream trajectory" is established that preserves bit-level integrity by bypassing traditional floating-point transformations. The methodology utilizes an integer-based stretching function to amplify microscopic variations, allowing for the observation of the Discrete Lyapunov Exponent (DLE) across multiple bit-scales.

The analysis employs spatio-temporal maps; where the X-axis represents iteration rounds and the Y-axis represents bit-window positions; to visualize the diffusion of input perturbations. This technique aims to identify the "Chaos Signature" and evaluate the structural sensitivity of the underlying map across various bit-resolutions. This work investigates how digital fixed-point constraints can degrade the statistical properties of chaotic ciphers and explores methods to identify these vulnerabilities.

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Interpretable Classification of Time Series Using Euler Characteristic Surfaces

Buddha Nath Sharma[1], Vishal Mandal[1], Salam Rabindrajit Luwang[1], Atish J. Mitra[2], Md. Nurujjaman[1], Sushovan Majhi[3]

[1]National Institute of Technology Sikkim, Department of Physics, Ravangla, 737139, India
[2]Montana Technological University, Department of Mathematical Sciences, Butte, MT 59701, USA
[3]George Washington University, Data Science Program, Washington, DC 20052, USA

Classification of time series is an active area of research in a number of fields. We introduce **Euler Characteristic Surfaces (ECS)** as a computationally efficient and interpretable topological descriptor tailored to this task. A scalar time series is first embedded into phase space via Takens delay embedding. The embedded point cloud is partitioned into K non-overlapping temporal blocks using our K**-window method**, and for each block an Alpha complex is constructed across a range of filtration scales r. The Euler characteristic $\chi = \sum_i (-1)^i C_i$ of each complex is assembled into a two-dimensional (r, k) surface — the ECS — which encodes topological structure simultaneously across scale and time at complexity $O(n + R{\cdot}T)$, far cheaper than persistent homology at $O(n^\omega)$, where $\omega < 2.373$.

We validate ECS on the **Rössler system** as it transitions from limit-cycle ($c = 2.3$) to strange-attractor ($c = 7.3$) dynamics (Fig. 1). The periodic regime yields a smooth, regular surface, while chaos produces pronounced irregularities with elevated χ at low filtration scales — a direct topological fingerprint of increased attractor complexity. We prove a stability theorem bounding the L_1 change in ECS under small perturbations of the input signal, and confirm empirically that inter-regime L_1 distances remain large even under 10% Gaussian noise.

Classification is performed using either a single ECS feature with a Youden-optimal threshold (maximum interpretability) or an AdaBoost ensemble of ECS-based decision stumps (improved accuracy). Applied to biomedical benchmarks, a *single* ECS feature achieves 98% accuracy on *ECG5000* (AUC $= 0.994$), far surpassing a recent persistent-homology pipeline (62%, AUC $= 0.90$) on the same dataset. AdaBoost raises this to 98.6% (AUC $= 0.999$), matching deep learning while every decision remains traceable to a specific (r, k) coordinate. Strong results extend to EEG seizure detection (*Epilepsy2*, 92.6%) and *TwoLeadECG* (94.1%). The ECS offers a principled, data-driven route to characterizing nonlinear and chaotic signals at the intersection of topological data analysis, time series analysis, and interpretable machine learning.

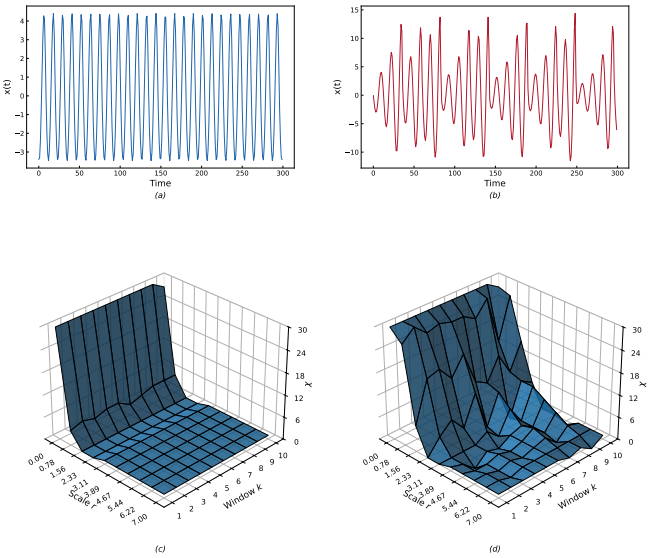

Figure 1: Time series and ECS for the Rössler system in the periodic ($c = 2.3$, left) and chaotic ($c = 7.3$, right) regimes. The ECS clearly distinguishes the two dynamical states.

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Thermodynamic Signatures and Phase Separations in Intermittent Active Matter

Budhaditya Banerjee[1], Dipjyoti Das[2], Rumi De[1]

[1]Department of Physics, IISER KOLKATA, Kalyani, India
[2]Department of Biology, IISER KOLKATA, Kalyani, India

The study of interacting active matter systems provides profound insights into non-equilibrium thermodynamics, particularly regarding phase transitions and collective motion. We investigate an interacting particle system driven by dichotomous active noise, where particles act as Markovian agents transitioning between self-propelled (active) and purely Brownian (passive) states at a variable switching rate K. By mapping the energetic variables of the system, we demonstrate that varying the fraction of active time induces a continuous flocking transition, macroscopically identifiable by a sharp "thermodynamic cliff" in the entropy production rate (EPR).

Furthermore, we explore the energetic consequences of varying the switching frequency K while holding the active probability constant. Through Langevin dynamics simulations, we observe a robust, non-monotonic dip in heat dissipation and mean squared velocity at intermediate switching rates. This indicates a timescale resonance where the internal motor switching perfectly aligns with external fluid drag, maximizing internal structural frustration and kinetic energy loss.

To formalize this mathematically, we develop a mean-field theory using Fokker-Planck equations. While the mean-field approximation successfully predicts the Power consumption and mean squared velocities in the high switching (annealed) limit, we show that it significantly diverges from the simulated dynamics in the slow-switching (quenched i.e. $K \to 0$) regime.

By analyzing velocity distributions and spatial pair-correlation functions, we reveal the physical mechanism behind this mean-field failure: a dynamic, motility-induced phase separation (MIPS). In the slow-switching limit, the system segregates into rigid, highly correlated clusters of active particles propelling as a unit, leaving behind localized aggregates of passive particles. These strong spatial correlations act as internal "bungee cords," forcing active agents to physically drag passive neighbors. This microscopic dynamic sorting ultimately restricts the macroscopic motor power the system can consume, proving that energy extraction in flickering active matter is an emergent property dictated by local mechanical traffic and collective variance, rather than independent active forces.

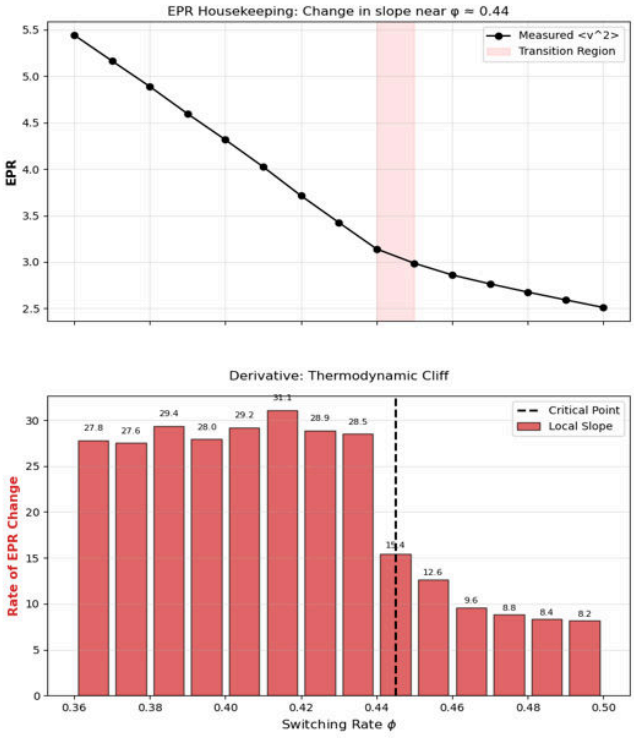

Figure 1: Macroscopic energetic signatures across the continuous phase transition, highlighting the distinct "thermodynamic cliff" in the entropy production rate (EPR).

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Accelerating Quantum State Through Continuous Measurement

J David Smith[1], V. K. Chandrasekar[1], and D. V. Senthilkumar[2]

[1]Centre for Nonlinear Science and Engineering, Department of Physics, School of EEE, SASTRA Deemed to be University, Thanjavur 613 401, Tamil Nadu, India.

[2]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram, 695 551, Kerala, India.

Steering an open quantum system toward its steady state efficiently is a central challenge in quantum control. Standard approaches exploit the Liouvillian spectral structure — notably, removing the slowest-decaying mode from the initial state to suppress the dominant relaxation bottleneck. Here we demonstrate an alternative and physically transparent route: continuous photon-counting measurement can serve as a powerful accelerator of quantum relaxation, connecting this phenomenon to the Anti-Zeno effect.

We study a quantum van der Pol oscillator subject to a coherent external drive, governed by the Hamiltonian $\hat{H} = -\Delta a^\dagger a + i\Omega(a - a^\dagger)$. Under projective measurement with outcome r, the post-measurement state $\rho_r = M_r \rho M_r^\dagger$ is shown to exhibit a modified decay rate toward the steady state. We establish that the key mechanism is the overlap of the post-measurement state with the slowest-decaying Liouvillian eigenmode: measurement outcomes that suppress this overlap yield accelerated relaxation, while those that enhance it retard it. The distribution of this overlap over stochastic measurement records directly encodes the probabilistic nature of the continuous measurement process, providing a clear diagnostic of Anti-Zeno physics.

To harness acceleration systematically, we integrate continuous photon-counting with quantum trajectory methods. By averaging over an ensemble of n stochastic trajectories — each conditioned on a continuous measurement record — we demonstrate that effective, robust acceleration of the ensemble-averaged state is achievable. This establishes a deep operational link between continuous measurement, quantum trajectories, and steady-state engineering. Our results open a practical pathway for measurement-assisted quantum control in driven-dissipative systems.

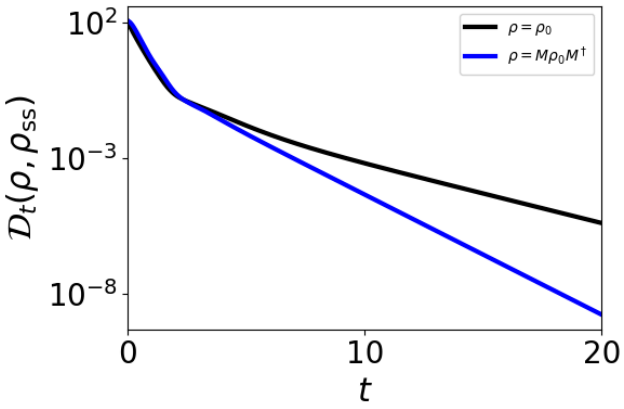

Figure 1: Trace Distance measure of density state of the given system.

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Modelling impact of regime shift environmental changes on a system of two interacting species

Debendra Nath Sarkar[1], Balakrishnan Ashok[2], Janaki Balakrishnan[1]

[1]Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560012, INDIA.
[2]Complex Systems & Soft Matter Physics LAb, Centre for Applied Sciences, International Institute of Information Technology Bangalore (IIIT-B), 26/C, Electronics City Phase-1, Hosur Road, Bengaluru 560100, INDIA.

We present some results [1] from our dynamical population model of two species of organisms competing for common resources, to understand the impact of sudden, drastic environmental changes [2] on a living ecosystem. The intrinsic growth rates of both species are taken to be time-dependent, and reflecting sudden environmental changes. The carrying capacity of the populations also have a nonlinear variation in time. Both contest and scramble-type competitions between the two species are considered.
Linear stability analysis of the system is performed, and Lyapunov spectra and basins of attraction computed, spanning varying parameter values. We find very interesting dynamical behaviour in different parameter regimes.

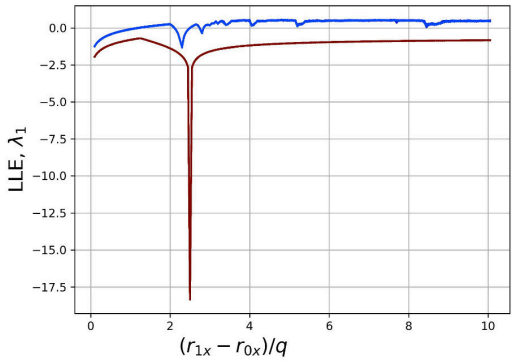

Figure 1: Largest Lyapunov exponent for the 2-dimensional system for 100 initial conditions showing coexistence of 2 different attractors. Colours indicate different initial conditions.

The change in growth rates in time triggered by environmental or climate changes are modelled by a ramp-like function, to simulate tipping to a new dynamical state.
We demonstrate that the system shows a regime-shift to co-existence between periodic and chaotic states in some parameter regimes, and in other parameter regimes we see amplitude death of one of the species when the other has multiple periodicities or is in a chaotic state.
Similar studies were also done for growth rates varying sinusoidally with time.
Our results could be used to explain experimental observations [3] published previously in the literature of lboratory studies on two species of bruchid beetles *Callosobruchus chinensis* and *C. maculatus* over several generations.

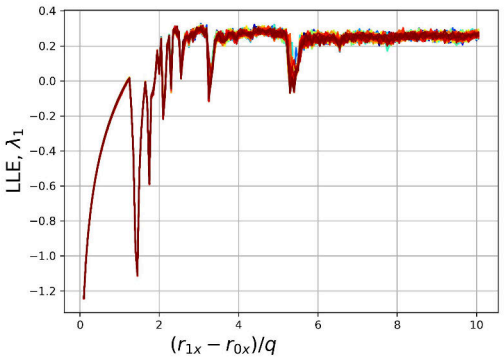

Figure 2: Largest Lyapunov exponent for the 2-dimensional system for a differet parameter regime, for 100 initial conditions showing coexistence of 2 different attractors. Colours indicate different initial conditions.

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Signatures of Chaos in a Quasi-Periodically Driven Quantum Impact Oscillator

Deepshikha Singh[1], **Soumitro Banerjee**[1]

[1]IISER Kolkata, India

Strange nonchaotic attractors (SNAs) have been observed in quasiperiodic driven systems, where the dynamics exhibit a fractal structure with negative Lyapunov exponents. In this paper, we apply it to an impact oscillator — a forced harmonic oscillator constrained by a wall. We find that a quasiperiodically forced impact oscillator, without damping, displays chaotic behavior. In particular, under grazing conditions, where the mass tangentially interacts with the wall, the system undergoes a sudden transition to chaotic oscillations.

Motivated by this classical behavior, we investigate whether such signatures of chaos persist in the corresponding quantum regime. To this end, we simulate the dynamics of the time-dependent quantum system using commutator-free exponential time propagators (CFETs)[1]. These propagators are derived using the Magnus expansion, and thus preserve unitarity of the evolution but avoid nested commutators. This approach provides an efficient and accurate alternative to conventional numerical schemes such as Runge–Kutta and split-operator methods. In contrast to Runge–Kutta techniques, which require small time steps to control error accumulation, CFETs achieve higher-order accuracy through exponential operator expansions, leading to improved numerical stability over long-time evolution. Furthermore, unlike split-operator methods, CFETs do not rely on separability of the Hamiltonian and are therefore applicable to more general time dependent systems. Higher-order CFET schemes can be constructed with error scaling of order Δt^n making them particularly suitable for driven quantum systems.

The initial state is taken as a Gaussian wave packet localized in the position basis. The time evolution is performed using CFET. From the time-evolved wave function, we calculate the Shannon entropy (which captures the spreading of wave function in position basis) from the probability density and use it as a time series.

The resulting entropy time series is analyzed using tools from nonlinear dynamics[2] to characterize the underlying behavior. We find that in the quantum regime, the Fourier spectrum of the dynamical observables reveals a continuous distribution, in contrast to the discrete peaks characteristic of regular motion. In addition, the application of the 0–1 test yields values close to unity. Furthermore, the system exhibits an initial exponential growth of the out-of-time-ordered correlator (OTOC), followed by saturation at longer times, indicating the onset of quantum chaos and further confirming chaotic behavior.

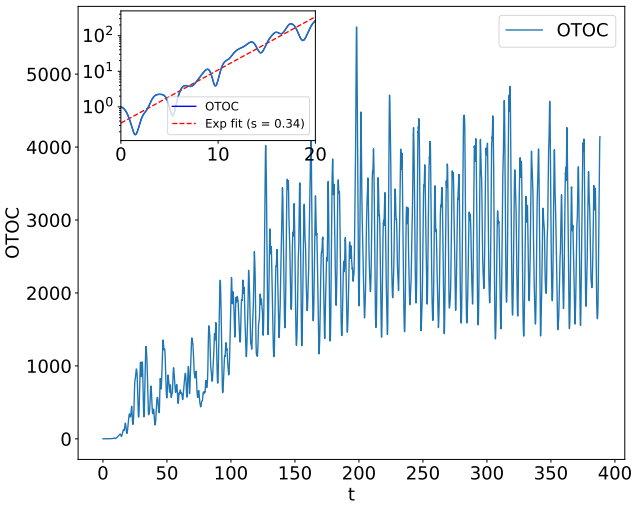

Figure 1: Plot of OTOC vs time, the exponential rise can be observed in the semi-log plot.

All these indicators consistently demonstrate the emergence of chaos in the quantum system under parameter regimes close to the grazing condition of the corresponding classical system.

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Symbiotic Dark-Bright Solitons in a Superfluid-Impurity System

Dileep K[1], S. Murugesh[1]

[1]Department of Physics, Indian Institute of Space Science and Technology, Thiruvananthapuram 695 547, India

It is well known that 2D localizations in a single component nonlinear Schrödinger equation (NLSE) are unstable due to transverse instabilities. This is because the dispersion of the wavepacket cannot be completely compensated for by the cubic nonlinearity. One way to sustain localizations in higher dimensions is to go beyond the standard self-focusing NLSE by including higher-order effects or modified nonlinearities, which effectively balance the transverse dispersion and stabilize 2D solitons.

Another route towards realizing localizations in 2D is through the two-component generalizations of the NLSE, which provides an additional degree of freedom for stabilizing solitons by compensating the transverse dispersion. A highly tunable experimental setting for realizing such multicomponent generalizations of NLSE is provided by the atomic Bose-Einstein condensates (BECs). The binary BECs have been experimentally observed and theoretically investigated for a variety of nonlinear phenomena such as symbiotic solitons in 1D and vortices in 2D.

Recently, a limit of the binary mixture has been experimentally realized, where one component is dilute and acts as an impurity in the superfluid [1]. Such superfluid-impurity systems have been shown to exhibit localizations in the impurity component in 1D using the mean-field model [2]. In this work, we investigate the dynamics of superfluid-impurity system confined to 2D and described by the coupled Gross-Pitaevskii equations (GPEs) [1, 2]

$$i\hbar\frac{\partial\psi_1}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + U_{11}|\psi_1|^2 + U_{12}|\psi_2|^2\right)\psi_1, \quad \text{(1a)}$$

$$i\hbar\frac{\partial\psi_2}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + U_{12}|\psi_1|^2\right)\psi_2, \quad \text{(1b)}$$

where U_{11} denotes the mean-field interaction between the atoms in state ψ_1 and U_{12} is the interaction between the superfluid and impurity atoms. We have neglected the interaction between the impurity atoms on account of its diluteness.

It can be shown using the linear stability analysis that the stationary homogeneous solution of the superfluid-impurity system is unstable with respect to periodic modulations. Using numerical simulations of the coupled GPEs, we observe that these perturbed stationary configurations evolve into stable symbiotic dark-bright (DB) solitons when the inter- and intra-component interactions are repulsive. Moreover, the interaction between two such DB solitons are shown to depend on the relative phase between the bright components of the composite solitons. In particular, when the phase difference between the solitons is zero, they coalesce, whereas out-of-phase solitons repel each other.

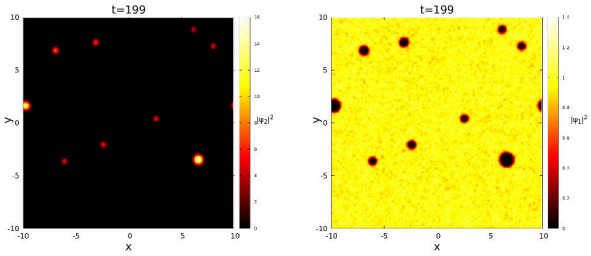

Figure 1: Dark-Bright solitons in a 2D superfluid-impurity system with repulsive contact interactions

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Decoding Tissue Self-Organization: A Mechanochemical Approach to Motility-Induced Phase Transitions

Dinesh Kashyap[1], Raj Kumar Manna[2], Sudipta Kumar Sinha[1*]

[1]Theoretical and Computational Physical and Biophysical Chemistry Lab, Department of Chemistry, Indian Institute of Technology Ropar, Rupnagar, Punjab, India-140001

[2]Biophysics and Biofluids Lab, School of Medical Science and Technology, Indian Institute of Technology Kharagpur, Kharagpur, India-721302

Biological tissues are highly adaptable living materials. Depending on how their individual cells behave, a tissue can act like a rigid, solid barrier or flow like a liquid. Understanding how cells collectively switch between these states is vital for explaining processes like embryo development, wound healing, and the spread of cancer. A key driver of these changes is the "motility-induced phase transition". This is a phenomenon where the active, self-propelled movement of cells causes them to spontaneously separate into dense, tightly packed clusters (solid-like) and loose, fast-moving regions (fluid-like). While the physical forces between cells are known to cause this, the way environmental chemical gradients guide this physical transition is not fully understood.

To explore this, we present an extensive computational framework that couples the Active Finite Voronoi (AFV) model [1] with a continuous chemical concentration field of Delta ligand of notch-delta signalling pathway. Crucially, our approach utilizes the finite Voronoi model rather than the standard Voronoi model. Standard Voronoi models enforce strict "confluency", meaning cells must always touch each other with no empty space in between. In reality, tissues often tear, and cells detach. The AFV model solves this by allowing for gaps, cell detachment, and non-confluent geometries. It accurately captures the physical mechanics of individual cell shapes, governed by how hard it is to stretch the cell membrane or change its internal area, while giving cells the freedom to break apart and migrate independently.

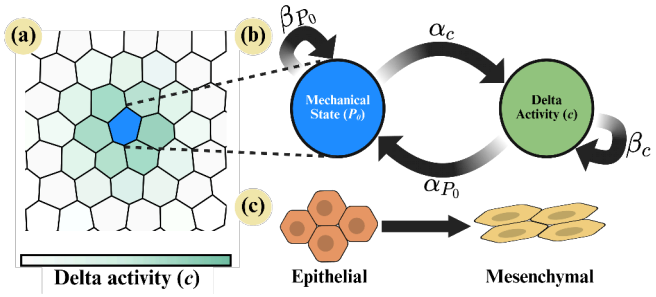

Figure 1: The schematic diagram illustrates the mechanochemical coupling between the Delta ligand concentration field and the Voronoi cell structure.

Our simulations demonstrate that coupling the finite Voronoi mechanics with a concentration field fundamentally alters how the tissue self-organizes. By tuning the baseline motility of the cells and their sensitivity to the chemical field, we map out a rich variety of collective behaviors. We observe that chemical gradients can heavily bias cell movement, causing them to slow down and gather in regions of specific concentration. This localized slowing triggers a sharp motility-induced phase transition: the uniform tissue dramatically separates into rigid, jammed islands of clustered cells surrounded by highly mobile, scattered cells. Ultimately, this work highlights how continuous environmental chemical signals work hand-in-hand with discrete cell mechanics to control the physical phase and migration of biological tissues.

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Nonlinear Dynamics of Pressure Drop Oscillations via Hopf-Pitchfork Bifurcation in Parallel Boiling Channel

Dipankar Das[1], Suneet Sing[1]

[1]IIT Bombay, Mumbai, India

Understanding flow instabilities in boiling channels is crucial for maintaining the operational safety and performance of thermal systems used in power generation, chemical processes, and advanced cooling technologies. Various instability phenomena are known to originate from different bifurcation mechanisms. For example, dynamic two-phase instabilities such as pressure-drop oscillations (PDO) and density-wave oscillations (DWO) are generally associated with Hopf bifurcations, while static instabilities, including Ledinegg instability and flow maldistribution, are typically linked to pitchfork or saddle-node bifurcations. Although earlier investigations have confirmed the presence of Hopf–Pitchfork bifurcation and demonstrated oscillatory responses in parallel boiling channel systems, a detailed examination of the system dynamics in the neighborhood of this bifurcation point has remained limited.

The present work addresses this gap through a systematic nonlinear dynamical analysis of a parallel boiling channel configuration. A nondimensional mathematical representation of two identical channels connected through a shared surge tank is considered. In this framework, the global operating mass flow rate (M_0) is treated as the principal bifurcation parameter, while the inlet subcooling temperature (T_1) serves as a secondary parameter for mapping stability boundaries in a two-parameter space. The resulting bifurcation structure demonstrates the simultaneous presence of symmetric and asymmetric steady solutions, with the Hopf-Pitchfork point identified as the location where Hopf and pitchfork bifurcation curves intersect.

Within the stable operating region, small disturbances diminish over time and the system settles into asymmetric steady states, indicating the loss of symmetry characteristic of pitchfork bifurcation. As system parameters move closer to the Hopf boundary, periodic solutions emerge from a supercritical Hopf bifurcation, giving rise to stable limit cycle oscillations. Continued variation of operating conditions leads to an increase in oscillation amplitude until a limit point of cycles (LPC) is encountered. At this stage, the previously stable limit cycle becomes unstable, and a new unstable periodic branch appears in conjunction with a branch point of cycles (BPC). A codimension-2 bifurcation analysis performed using M_0 and T_1 clearly identifies the regions separating stable and unstable behavior in the parameter domain.

Beyond the LPC threshold, the system develops persistent oscillations of large amplitude, characterized by increasing temporal variations in the nondimensional mass flow rate. These oscillations eventually stabilize into sustained pressure-drop oscillations, as illustrated by the corresponding phase trajectories in the operating mass-flow–pressure plane. Overall, the study establishes a coherent sequence of dynamical transitions-from steady equilibria to periodic oscillations and ultimately to large-amplitude PDO—driven by nonlinear processes occurring near the Hopf-Pitchfork bifurcation point in parallel boiling channels.

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Emergence of Extreme Spikes in Periodically Forced Coupled Excitable Neurons

Gobi Krishnan K[1], **Suresh R**[1]

[1]Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613 401, India

Extreme events, rare, large-amplitude deviations from typical system behavior, are a hallmark of nonlinear dynamics and carry significant consequences in both physical and biological contexts. In neuronal systems, such events manifest as abnormally large collective spikes that arise near critical dynamical transitions, and are closely associated with pathological phenomena such as epileptic seizures.

In this study, we investigate the emergence of extreme events in a network of coupled FitzHugh–Nagumo (FHN) excitable oscillators driven by external periodic forcing of the form $I_0 \sin(\omega t)$. The model is described by the following set of equations.

$$\dot{x}_i = x_i(a_i - x_i)(x_i - 1) - y_i + k\sum_{j=1}^{N} A_{ij}(x_j - x_i) + I_0 \sin(\omega t)$$

$\dot{y}_i = b_i x_i - c_i y_i, \quad i = 1, 2, 3, \ldots, N$ where x_i and y_i denote the fast and slow variables, respectively, and k represents the coupling strength.

Through bifurcation analysis, time-series characterization, and statistical quantification, we demonstrate that deterministic periodic forcing alone, without noise, time delays, or complex network topology, is sufficient to trigger rare, high-amplitude spikes under appropriate parameter conditions. Below a critical forcing amplitude, the network exhibits regular bounded oscillations; beyond it, extreme-event behavior emerges abruptly.

This finding carries direct neuro-physiological relevance: rhythmic thalamic drive to the cortex, when excessive or destabilized, can synchronize large neuronal populations and precipitate the kind of abnormal electrical discharges characteristic of seizure activity. Our results thus offer a parsimonious, deterministic mechanism for extreme event generation in coupled excitable systems, a perspective that contrasts with and complements prior work attributing such behavior to stochastic noise, interior crises, synaptic interactions, or topological effects. These insights may advance understanding of seizure-onset dynamics and inform the design of intervention strategies in neural network models.[5, 6]

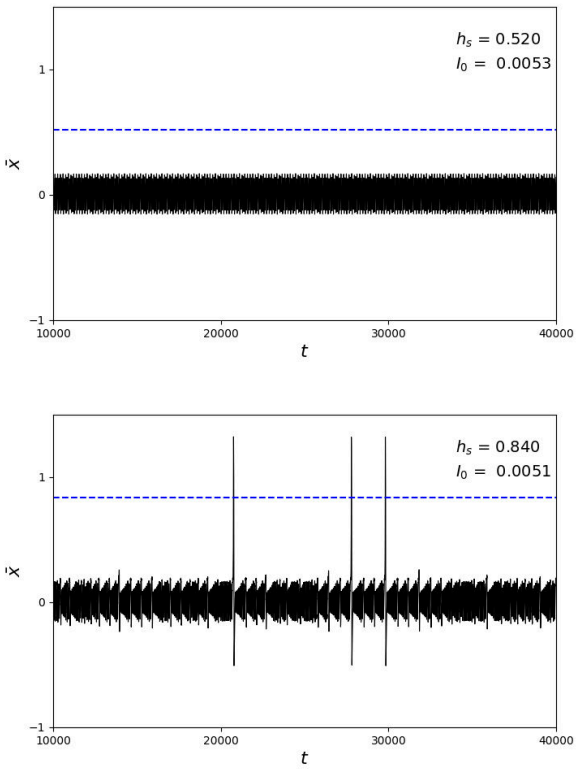

Fig. 1. (a) Time series showing bounded oscillations without forcing. (b) Emergence of rare, large-amplitude spikes at higher forcing amplitude. The dashed line indicates the statistical threshold used to classify extreme events.

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Measurement-Induced Synchronization in Quantum Spin Oscillators

Gokilavarthini R[1], Chandrasekar V K [1], Senthilkumar D V [2]

[1]Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613 401, India
[2]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram 695551, Kerala, India

Synchronization in quantum systems has attracted considerable interest as a fundamental manifestation of collective behavior in nonequilibrium dynamics. It is typically realized in self-sustained oscillators through coherent or dissipative coupling, where the interplay of driving, damping, and quantum fluctuations gives rise to correlated dynamics between subsystems. Minimal models, such as spin-1 oscillators, provide a natural framework to explore synchronization in the deep quantum regime.

However, a key challenge arises in such minimal systems: symmetric dissipation can inhibit synchronization between identical units in the absence of direct coupling. Consequently, most existing approaches rely on engineered interactions or parameter asymmetry to establish correlations, limiting the realization of synchronization in systems without explicit coupling.

The dynamics of such systems can be described within the Lindblad framework,

$$\dot{\rho} = -i[\hat{H}, \rho] + \sum_j \mathcal{L}_j \rho + \kappa \mathcal{D}[\hat{M}]\rho,$$

where $\mathcal{L}_j$ represents local dissipators that generate self-sustained oscillations in each subsystem, and

$$\mathcal{D}[\hat{M}]\rho = \hat{M}\rho\hat{M}^\dagger - \frac{1}{2}\{\hat{M}^\dagger\hat{M}, \rho\}$$

is the Lindblad dissipator associated with a measurement channel.

Here, we demonstrate that continuous measurement backaction provides an alternative route to synchronization without direct interaction. By introducing a collective measurement channel acting on a phase-sensitive observable, we show that measurement backaction alone can generate correlations between otherwise uncoupled oscillators and drive the emergence of synchronized dynamics. Notably, this mechanism exhibits a non-monotonic dependence on measurement strength, with an optimal regime at intermediate coupling and suppression at strong measurement due to the quantum Zeno effect.

These results establish measurement backaction as a versatile and tunable resource for engineering collective dynamics in open quantum systems. This approach opens new possibilities for realizing synchronization in platforms where direct coupling is weak or undesirable, with potential applications in quantum control, distributed quantum sensing, and scalable quantum networks, where indirect mechanisms for generating correlations are advantageous.

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Attractors dynamics of non-reciprocal systems

Hareesh J[1,2], Sitabhra Sinha[1,2]

[1] The Institute of Mathematical Sciences, Chennai, India
[2] Homi Bhabha National Institute, Mumbai, India

Structure-Function correspondence is a problem of interest in various domains of science and engineering. It is particularly intriguing in biological systems because unlike engineered control systems, biological structures are assimilated by evolutionary forces, and unfolded via development, all the while retaining, adapting and modifying functionality. Dynamical systems offer a powerful framework to model interacting systems across varying spatial and temporal scales. The criteria for convergence and stability of the asymptotic solutions is partially understood for a wide variety of systems with reciprocal interactions. However, biological systems are often non-reciprocal, which limits our understanding of the role played by the network topology in modulating attractor dynamics.

In order to study the behavior of such systems, we utilize two key motif structures, the combination of which enables us to construct a class of feed-forward networks where all the fixed points attractors can be tabulated and their basin size can be kept track of. The role of distinct topological features that eventually shape the attractor dynamics is systematically explored. Unlike undirected networks, incoherent signaling in directed networks could either increase or decrease the basin entropy and the stability of attractors. Upon addition of feedback interactions that are designed to induce frustration in the dynamics, fixed points lose their stability giving rise to limit cycle and chaotic attractors.

The complexity and distribution of computational schemes in biology permits highly evolvable and adaptable systems. For the same reasons however, it is difficult to scale biological models starting from a purely structural description. Structural features and functional outcomes are often related, but it is not always feasible to derive one from the other. Our results reinforce the growing belief in the primacy of mechanisms of controllability and robustness in appropriate representational spaces, and points to the limitations of meaningful inferences at node level operations.

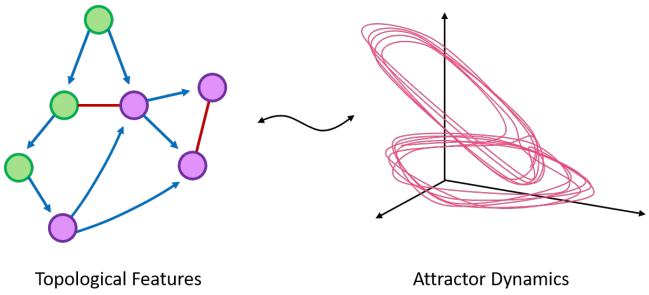

Figure 1: Systematic exploration of dynamical outcomes associated with distinct topological features

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SNA-Based Secure Wireless Communication Using Arduino Uno and 433 MHz RF Modules

Haroon Raseeth A[1], Rizwana R[2]

[1,2]Department of Physics, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600 048, India

This work presents the design and implementation of a simple non-autonomous electronic circuit, capable of generating strange nonchaotic attractor (SNA) for secure communication applications. A second order non-autonomous electronic circuit with quasiperiodic forcing is constructed to produce SNA dynamics, which are characterized by aperiodic behavior with Lyapunov exponents and '0-1 test'. The generated SNA signal is utilized as a carrier to mask the information signal, enabling secure transmission.

A wireless transmitter–receiver setup is developed to communicate the masked signal. At the receiver end, the original information is successfully recovered through synchronization between the drive and response systems. The existence of SNA is verified numerically using computational tools including MATLAB/Python and Multisim, where the results are closely matched with experimental observations.

Synchronization techniques are implemented and analysed to ensure accurate signal recovery. Finally, a comparative analysis is performed to evaluate the effectiveness of nonlinearity-based communication, demonstrating its advantages over conventional chaotic systems in terms of robustness, security, and parameter sensitivity.

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A Combinatorial Metaplex Framework for Identifying Higher-Order Interactions in Complex Networks

Hiren J. Dhameliya[1], Udit Raj[2], Sudeepto Bhattacharya[1]

[1]Shiv Nadar Institution of Eminence (Deemed to be University), Gautam Buddha Nagar, Uttar Pradesh, India.
[2]Indian Institute of Technology, Kanpur, Uttar Pradesh, India.

Complex systems consist of interacting units; their interactions may be pairwise (involving two units) or higher-order (involving more than two units simultaneously). Graphs are used to model pairwise interactions and represent such systems as networks in which units are represented as vertices and their interactions as edges. Simplicial complexes can capture and model higher-order interactions (HoIs) and represent such systems as higher-order networks comprising simplices. A simplex is defined as a finite subset of a vertex set. A simplicial complex is a collection of simplices that is closed under subset inclusion, that is, whenever a simplex belongs to the collection, all of its subsets belong to it. The clique complex of a graph is a simplicial complex where a simplex is included whenever its vertices form a clique in the underlying graph. In classical graph-theoretic and simplicial-complex models, vertices are treated as structurally indistinguishable objects. However, in many real-world systems, vertices possess internal structure (e.g., city populations in transportation networks or species abundance in ecological networks), and their intrinsic properties influence the formation of HoIs in the system. To address this limitation, we introduce the combinatorial metaplex, consisting of two interacting components: an underlying simplicial complex and a cocentration layer. The simplicial complex defines a boundary-compatibility criterion for higher-order simplex inclusion. The internal structure of the vertices gives rise to the concentration layer, in which a concentration map (i.e., the weight map) assigns a discrete measure to each vertex. The weight map is extended over a simplicial complex via fractional weight contribution maps. We prove a weight-distribution theorem for simplicial complexes stating that the total weight assigned to vertices equals the total weight assigned to facets. For higher dimensions (greater than 1), we introduce a threshold-based inclusion criterion to determine which boundary-compatible simplices (i.e., simplices whose boundary simplices are present in the complex) are included as true HoIs. We illustrate the proposed framework using data from an ecological network and compare the true HoIs identified by the framework with those produced by the clique complex, in which a HoI is included for every boundary-compatible simplex.

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Soliton Excitation in a Frustrated Asymmetric Spin Ladder

Ibrahim A.R[1], Parasuraman E[1]

[1]Department of Physics, School of Advanced Sciences, Vellore Institute of Technology, Vandalur-Kelambakkam Road, Chennai 600127, Tamil Nadu, India

The spin ladder system is an excellent model for understanding low-dimensional magnetic systems and has attracted considerable attention in recent years, since it bridges the gap between one-dimensional and two-dimensional magnetic systems. A spin ladder system can exhibit frustration due to competing ferromagnetic and antiferromagnetic couplings, leading to a variety of exotic ground-state phases and the formation of localized excitations, such as solitons. Importantly, frustrated ladder-type magnetic systems are observed in several real materials, including the quasi-one-dimensional cuprate $(La,Y,Sr,Ca)_{14}Cu_{24}O_{41}$ and $BiCu_2PO_6$. In this article, we study the nonlinear excitations and soliton collision dynamics in a frustrated asymmetric ferromagnetic two-leg spin ladder. We consider a Heisenberg Hamiltonian describing a frustrated asymmetric two-leg spin ladder with competing exchange interactions. Where both legs and rungs are ferromagnetic, but the diagonal exchange is antiferromagnetic. We obtain the discrete nonlinear equation of motion using the Holstein-Primakoff transformation and Glauber's coherent state. The discrete Hirota bilinearization method is then used to construct the one-soliton and two-soliton solutions of the discrete nonlinear Schrodinger equation. To ensure experimental relevance, we consider parameters consistent with known ladder materials, with exchange coupling constants J_{leg}, J_{rung}, and $J_{diagonal}$ being of similar strength. The obtained soliton solutions reveal the influence of frustration and asymmetry on nonlinear energy localization, while clarifying how competing interactions govern the formation, propagation, and stability of coherent structures in low-dimensional ladder systems. In addition, the analysis of soliton collisions provides insight into interaction dynamics and energy transport, high- lighting the potential of these systems to support robust spin excitations relevant for magnonic and spintronic applications

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A Numerical Study Of Nonlinear Spin Excitations in Heisenberg Ferromagnets

Imam Aashif B[1], Parasuraman E[1*]

[1]Department of Physics, Vellore Institute of Technology, Chennai Campus, Tamil Nadu 600 127, India

Nonlinear spin excitations in Heisenberg-type ferromagnetic systems have long been of interest, mainly because they help in understanding how collective magnetic behavior emerges and evolves. In these systems, localized structures such as solitary waves and solitons appear quite naturally from the nonlinear interaction of spins, especially when the system is viewed under a continuum approximation. Although many earlier studies focus on bilinear exchange interactions, real materials are often more complicated, and higher-order effects like biquadratic and octupole–dipole interactions can play a noticeable role in shaping the dynamics.

In this work, we take up a higher-order nonlinear Schrödinger-type equation [1] that arises within the semiclassical description of anisotropic Heisenberg ferromagnets with additional interactions and spatial variations. The focus is on understanding the kind of nonlinear evolution this equation can support.

For this purpose, the Fourier split-step method [2] is considered as a numerical tool to study the system. The idea is to follow how localized wave structures evolve and propagate when higher-order effects and inhomogeneities are present, and to see how these factors influence the overall spin dynamics.

It is expected that such an approach will offer a clearer picture of how complex interactions affect nonlinear spin excitations, and may be useful in the broader context of studying realistic magnetic systems, particularly those relevant to spintronic applications.

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Neurochaos Learning from The Double Pendulum

Sri Uma Maheshwari V[1], Jyoti Prakash Nayak[1], Nithin Nagaraj [2]

[1]National Institute of Science Education and Research (NISER), Bhubaneswar
[2]Complex Systems Programme, National Institute of Advanced Studies (NIAS), IISc. Campus, Bengaluru

Neurochaos Learning (NL) is a brain inspired learning algorithm that uses chaotic neurons in a single layer [1] and yields state-of-the-art classification performance. Drawing inspiration from biological neurons which are known to exhibit chaos, neurochaos learning implements its architecture by performing nonlinear feature transformation. Until now, NL architectures used various mathematically simulated chaos from 1D maps such as the Generalized Lüroth Series (GLS) as neurons. In this study, instead of GLS neurons, we employ real physical data from a double pendulum, a well known chaotic system to perform the feature transformation in Neurochaos Learning for classification on 8 publicly available datasets.

The Double Pendulum set-up consists of two rigid rods, connected between them and pivoted to a fixed support set up on an optical bread board, using well greased hinges. To facilitate visual tracking, the rod ends were marked with distinct colors, red and blue. Using a phone mounted on a tripod stand, multiple 30 to 45 second videos were captured by releasing the rods from different initial angles. The trajectory data was extracted using a custom OpenCV-based color detection algorithm (see Fig. 1).

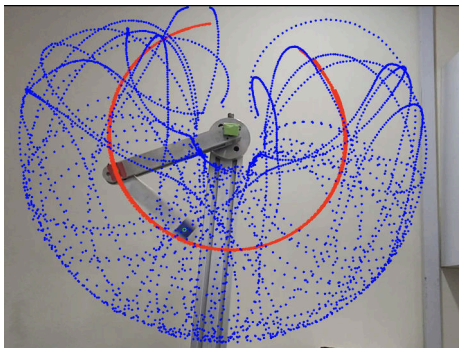

Figure 1: The Double Pendulum. The movement of the two rigid rods are depicted in *red* and *blue*. The chaotic blue trajectory is used in Neurochaos Learning in this study.

The Tracking Algorithm used predefined HSV (Hue-Saturation-Value) ranges to generate masks that isolated the red and blue markers, which were refined using erosion and dilation processes to remove noise, after which the contours were selected. The centroid of the largest contour was computed to obtain the exact (x, y) coordinates.

To obtain **Results** a highly chaotic trajectory (Lyapunov value: 3.18 nats/sec) recorded at 240 fps was used to replace the GLS neuron in the Neurochaos feature extraction algorithm of the ChaosNet NL architecture [1]. This was run in a high training sample regime: 80%-20% train-test split and 5-fold cross validation. The hyperparameter ϵ was tuned in the range of 0.0 and 0.5 (step-size $=$ 0.001) to find the value at which the macro F1 score is highest. We compare the classification performance between the GLS-neuron [2] and the Double Pendulum (DP) based NL architectures (Table 1) for the 8 datasets.

Table 1: GLS vs. Double Pendulum based Neurochaos Learning – Best Macro F1-scores and corresponding tuned hyperparameter ϵ for classification tasks on 8 datasets.

Dataset	**GLS F1**	**DP F1**	**Tuned ϵ**
Iris	1.000	0.895	0.500
Ionosphere	0.860	0.848	0.482
Wine	0.976	0.952	0.159
Bank Note	0.845	0.813	0.500
Haberman's Survival	0.560	0.621	0.167
Breast Cancer	0.927	0.982	0.356
Statlog (Heart)	0.738	0.862	0.164
Seeds	0.845	0.853	0.221

From Table 1, we infer that physical source of chaos (the Double Pendulum trajectory) for Neurochaos Learning architecture yields comparable (and at times superior) classification performance when compared with mathematical chaos (GLS).

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Insights into Nonlinear Stiffness and Dynamics of Living Tissues from Spring-Mass Systems and Semiflexible Polyelectrolytes

Jobin Josey[1] and Balakrishnan Ashok[1]

[1]Complex Systems & Soft Matter Physics Lab, Centre for Applied Sciences, International Institute of Information Technology, Bangalore (IIIT-B), 26/C Electronics City, Hosur Road, Bangalore 560100, India

Living systems such as muscle tissue exhibit dynamics ranging from regular oscillations to chaos, rooted in the nonlinear mechanics of their macromolecular constituents. To capture the behaviour, we study a mass suspended symmetrically between two springs with endpoints free to move in the plane, considering both Hookean and non-Hookean springs — showing softening or hardening stiffness depending on the parameter regime — under free and forced oscillations with and without damping.

Nonlinear interactions in such systems naturally give rise to complex behaviour, including transitions between chaotic, quasi-periodic, and periodic states. These transitions are characterised using bifurcation diagrams, Poincaré sections, and largest Lyapunov exponents, which map the system's response across parameter space and reveal how small changes in forcing amplitude or frequency drive shifts between distinct dynamical regimes [4, 5]. Additional modifications to the system, such as incorporating a non-Hookean spring constant, give rise to rich nonlinear phenomena, including jump discontinuities, bistable responses, and hysteresis loops, where the system's steady state depends on the direction of forcing. The nonlinear spring constants are motivated by prior work on carbon nanotube interactions [2]. Our model aims to capture the realistic elastic properties of living tissues and predict their dynamical regimes. The frequency response shows clearly separated stable and unstable branches, with amplitude peaks shifting toward lower frequencies as forcing grows — a softening behaviour characteristic of living tissues (Fig. 1).

To connect the mechanical model to a realistic biological scenario, we model muscle tissue as a semiflexible polyelectrolyte chain using the wormlike chain framework with a double-screening mean-field approach.[1, 3, 6]. We examine how salt concentration tunes effective stiffness across biologically relevant regimes, enabling a direct mapping of the nonlinear spring constant to physiological conditions [6]. In summary, the confined wormlike chain model links molecular-level parameter variations to the complex dynamics of the spring-mass system.

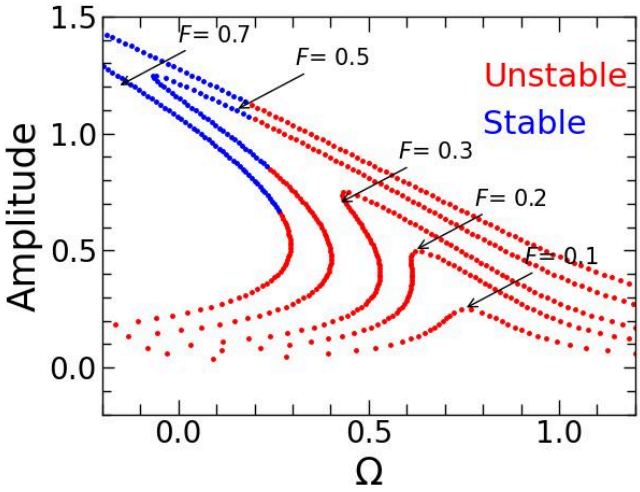

Figure 1: Frequency response of a non-Hookean mechanical oscillator for varying forcing amplitudes using the perturbation approach, with contraction ratio $\alpha = 0.2$, damping $\eta = 0.1$, $\omega_0 = 1$,and $\varepsilon = 1$ [4].

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Extreme events in an Active Fluid Medium

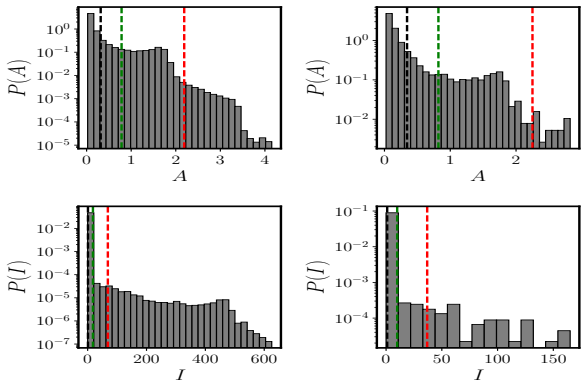
Joydeep Das, Abhishek Chaudhuri and Sudeshna Sinha

Indian Institute of Science Education and Research Mohali, Sector 81, SAS Nagar, Punjab, India

Extreme events are uncorrelated, rare but recurrent, large deviations of system's dynamics with respect to the nominal behaviour of the system. Such events are ubiquitous and highly impactful, and so their study has garnered wide-ranging interest.

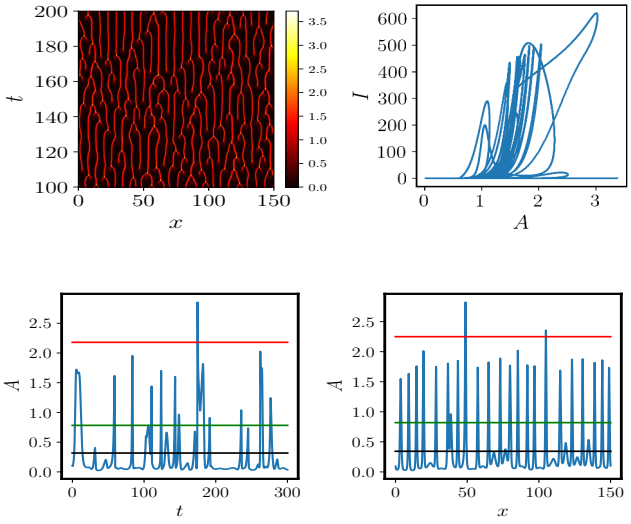
Another active research direction is pattern formation, and this is significant in systems ranging from biology to galaxies. Motivated by the dynamics of the actomyosin cell cortex, here we consider an active fluid system involving two distinct chemical species that regulate active stress. One species is slow diffusing and the other is fast diffusing, and the growth of the fast-diffusing species is modelled using a nonlinear logistic term. In an earlier study we had obtained and analyzed the diverse range of patterns emerging in this system, including pulsatory patterns, stationary patterns, robust symmetry-breaking chimera states and merging-emerging soliton-like structures [1].

Now we focus on the emergence of extreme events in this active fluid system, and demonstrate the presence of extreme events in the temporal evolution of the concentrations, as well as in the spatial profile of the system, through examination of the time-series, bifurcation diagrams and the probability distribution functions of the concentration of the two species.



Probability distribution of the values of variable A (top) and I (bottom): tracked over time, at a specific spatial location (left); tracked over space, at a specific time instant (right).

We also explore the change in extreme event occurrences under varying Péclet number and strength of the nonlinear growth term, and find that the rare and uncorrelated extreme concentration build-ups are found in regimes of merging-emerging soliton-like dynamics and spatio-temporal chaos. We also find clear evidence of bunching of extreme events, through investigations of the inter-event interval distributions and return maps.



Kymograph , phase portrait, time series and spatial snapshot of species A, for merging-emerging soliton-like dynamics. Here the average value μ of A is shown with a black line, and $\mu + \sigma$ and $\mu + 4\sigma$ (where σ is the standard deviation) with a green and red line respectively.

Lastly, in order to gain further understanding of the extreme events, we investigate a modified mode-truncated reduced order model of the system, and demonstrate that it also exhibits temporal extreme events. The emergence of these events is correlated with the sudden expansion in attractor size, as evident in the bifurcation diagram. These results give new insights into the occurrence of extreme events in active fluid systems.

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Nonlinear Stability and Power Dynamics in 2D PT-Symmetric Sinusoidal Couplers

Jaseera C P[1,2], Aysha Muhsina K[2], Rashida T N K[1]

[1]Govt Arts and Science College, Kozhikode, University of Calicut, Kerala, India, 673018.
[2]Govt College Madappally, Kozhikode, University of Calicut, Kerala, india, 673102.

This study systematically investigates the behavior of nonlinear waves in PT-symmetric and broken PT-symmetric regimes, emphasizing eigenvalues, eigenfunction stability, power exchange, Poynting vector and phase evolution. Below the threshold potential, solitons remain stable with real eigenvalues, small valued phase angle which indicates the balance between coupling and gain/loss in the system, constant phase evolution of eigenmodes, smoothly varying energy flux and symmetric waveforms, exhibiting well-defined power oscillations between the two coupled channels. However, as the system surpasses the PT-symmetry breaking threshold, eigenvalues become complex and eigenfunctions become asymmetric, deviating from Gaussian-like profiles and leading to unidirectional power transfer and instability.

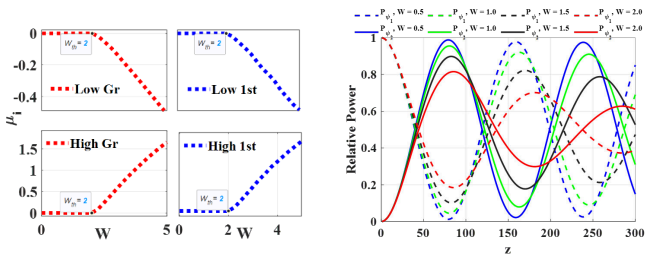

Figure 1: (a): μ_r vs W at $C = 2$ (b): Power switching between coupled waveguides

Numerical stability analysis using the Bogoliubov-de Gennes (BdG) method, supported by eigenvalue computations and perturbation techniques, confirms the stability of beams in the $2D$ optical system. The phase structure of the eigenstates provides further insight into stability conditions, with abrupt phase shifts correlating with instability onset. Additionally, the 2D generalization reveals that dimensionality alone does not necessarily increase the instability threshold, highlighting the complexity of PT-symmetric nonlinear systems. These findings contribute to a deeper understanding of soliton behavior in PT-symmetric media, with potential applications in optics and Bose-Einstein condensates, where controlled stability and power dynamics are crucial.

The PT-symmetric nonlinear system explored in this study demonstrates key functionalities that are directly applicable to advanced photonic technologies. The observed power switching behavior, along with tunable oscillation frequencies governed by the coupling strength, nonlinearity and imaginary potential, offers promising routes for realizing optical isolators and nonreciprocal light transmission—essential components in integrated photonic circuits enabling unidirectional signal flow. Notably, the system's ability to sustain stable solitonic states below the gain/loss threshold provides a robust platform for all-optical switching, logic gate implementation, and nonlinear signal modulation—critical for ultrafast optical computing and on-chip data processing. Moreover, the nonlinear suppression of power exchange at higher β values suggests opportunities for reconfigurable power routing and energy localization, which are beneficial in applications such as laser beam shaping and LiDAR-based beam steering. The identification of distinct stability thresholds contributes valuable insight for soliton-supported optical communication systems, particularly for mitigating dispersion over long distances.

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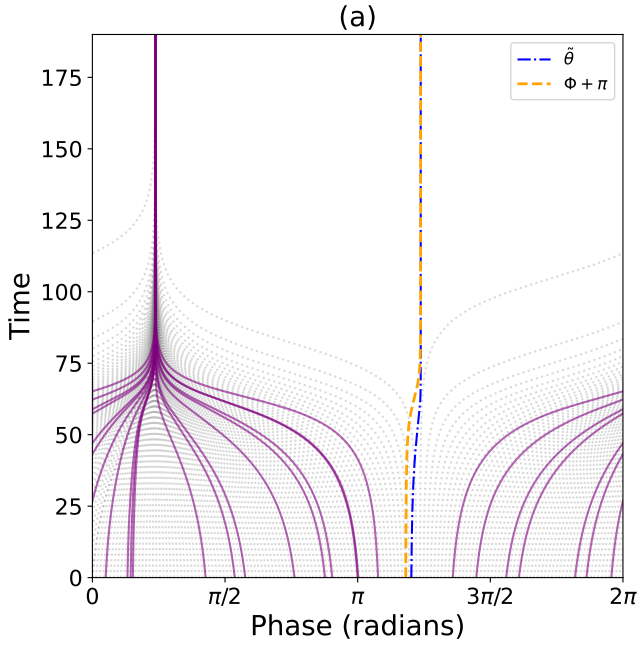
Low-dimensional Watanabe-Strogatz approach for Kuramoto oscillators with higher-order interactions

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

The Watanabe-Strogatz (WS) theory provides a low-dimensional and exact description of the dynamics of a finite population of identical Kuramoto oscillators via Möbius transformation. In this work, we develop a unified WS framework for a broad class of identical Kuramoto models incorporating pairwise and higher-order interactions, along with their higher harmonics [1]. We demonstrate that the evolution of the WS variables coincides with that of the corresponding mean-field order parameters. Unlike the Ott–Antonsen(OA) ansatz, which is exact only in the thermodynamic limit, the WS formulation remains exact for finite-size systems, offering a more general and robust description. Moreover, we show that the poles of the Möbius transformation define the basin boundaries separating global and cluster synchronized states. Numerical simulations further reveal the evolution of these basin structures, providing deeper insight into the collective dynamics of such oscillator systems.



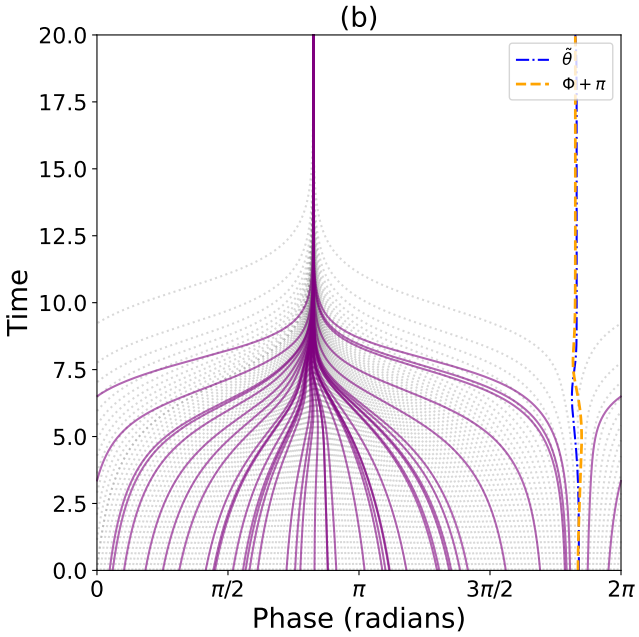


Figure 1: Evolution of basin boundaries for specific values of parameter for a given Kuramoto Model.

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Community Detection in Financial Hypergraphs

Jerry David[1], T. Di Matteo[2,3,4], Sarika Jalan[1]

[1]Complex Systems Lab, Department of Physics, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore 453552, Madhya Pradesh, India
[2]Department of Mathematics, King's College London, Strand, London WC2R 2LS, United Kingdom
[3]Centro Ricerche Enrico Fermi, Via Panisperna 89A, 00184 Rome, Italy
[4]Complexity Science Hub Vienna, Josefstädter Straße 39, 1080 Vienna, Austria

Stock markets, as paradigmatic examples of complex systems, have traditionally been modeled using pairwise network science to uncover hidden dependencies between stocks. However, real-world interactions are often multi-faceted and non-binary. We focus on higher-order interactions in market and use information theoretic measures to quantify the extent of such interactions.

Here, we extend the functional analysis of the Bombay Stock Exchange (BSE) by employing hypergraph theory to model higher-order (triadic) interactions over a 12-year period. We use adjusted closing price time series from 2010 to 2022, construct higher-order interaction networks(hypergraphs) from them [1]. We use a community detection algorithm which combines few of the existing techniques to uncover the community structure of the triadic network.

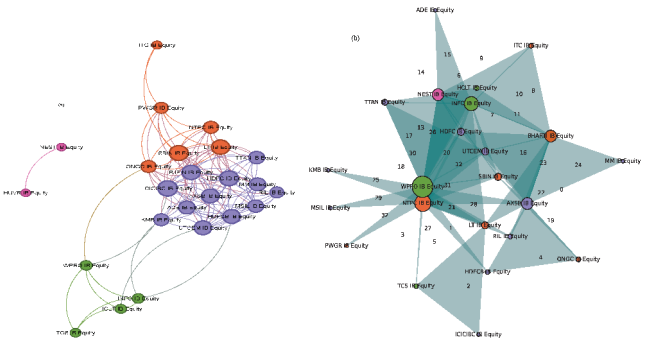

Figure 1: The visualization of the network structures: (a) pairwise, (b) higher order. The color is chosen so that for the pairwise network, members of the same community have the same color. The same color pattern is followed in the higher-order case, too. Both pairwise and higher-order networks are for the 27th window (1 June 2020 to 2 November 2020) for BSE market.

Our findings demonstrate that triadic community structures are highly dynamic, showing negligible resemblance to traditional sector-wise partitions and systematic disagreement with the pairwise community structure as measured by the adjusted rand indices. We further investigate the relationship between modularity and the degree distribution exponent within the triadic hypergraph, identifying "outstanding" stocks that disproportionately influence higher-order connectivity.

From a financial perspective, these results suggest that while groups of companies exhibit strong, consistent functional interactions, these clusters are transient rather than static. This lack of long-term stability in higher-order groupings aligns with the Efficient Market Hypothesis (EMH), suggesting that the market rapidly incorporates information, preventing specific triadic clusters from maintaining persistent collective advantages. This study highlights the necessity of higher-order analysis in understanding the fluid, competitive nature of emerging markets.

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Bifurcations of Invariant Closed Curves

Jessica Das[1], Viktor Avrutin[2], and Soumitro Banerjee[1]

[1] Indian Institute of Science Education & Research, Kolkata, India
[2] University of Stuttgart, Germany

An invariant closed curve (ICC) in a Poincaré section corresponds to a two-frequency torus in the phase space of a continuous-time dynamical system. If the two frequencies are commensurate, the closed curve is formed by the union of a node, a saddle, and the unstable manifold of the saddle, in case of stable ICC. ICCs can be unstable as well. If the two frequencies are incommensurate, the ICC is formed by the drift ring.

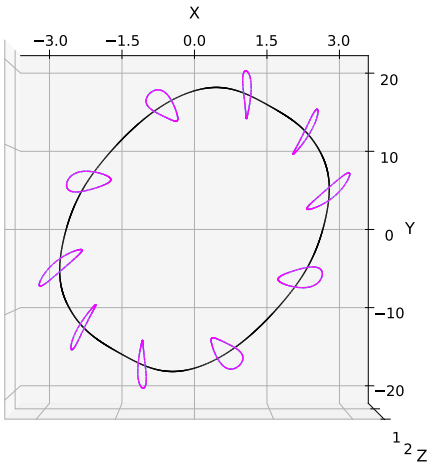
We investigate the different ways such an ICC (and hence the torus in continuous time) can bifurcate. Earlier work have investigated the process of doubling of an ICC [1, 2]. In this work, we investigate the occurrence of local bifurcations, such as saddle-node, transcritical, pitchfork, and Neimark-Sacker bifurcations of ICCs of both types.

In all cases, we start from a stable ICC—either mode-locked or quasiperiodic, which becomes unstable at a critical parameter value. We show that in the case of a pitchfork bifurcation, two stable ICCs are born; in case of a transcritical bifurcation, a stable and an unstable ICC exchange stability; and in case of a saddle-node bifurcation, a stable and and unstable ICC merge and disappear.

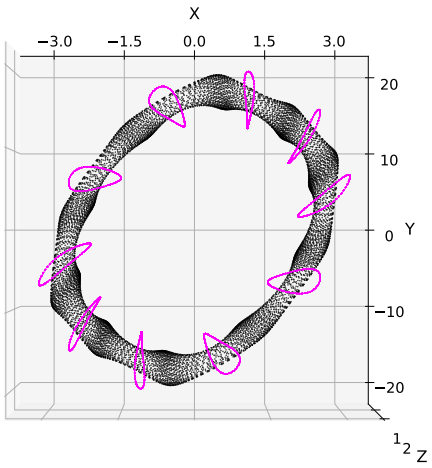
Here we briefly illustrate the Neimark-Sacker bifurcation, which is shown to occur in the map

$$
\begin{aligned}
x_{n+1} &= x_n + h y_{n+1}, \\
y_{n+1} &= y_n + h\big((\lambda + z_n + x_n^2 - \beta x_n^4) y_n - \omega_0^2 x_n\big), \\
z_{n+1} &= z_n + h\Big(b(\epsilon - z_n) - k y_n^2\Big).
\end{aligned}
$$

This system exhibits a quasiperiodic ICC for $\beta = 0.096$, coexisting with another quasiperiodic ICC with 10 rings. When the parameter is reduced to 0.094, the inner ICC becomes unstable and a three-frequency quasiperiodicity develops through a Neimark-Sacker bifurcation (Fig. 1).



(a) $\beta = 0.096$



(b) $\beta = 0.094$

Figure 1: Neimark-Sacker bifurcation of ICC. Parameters $h = 0.1$, $\lambda = -2.47$, $\omega_0 = 2\pi$, $b = 1$, $\epsilon = 4$, $k = 0.02$.

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Probing chaos and thermalization through out-of-time-ordered correlators in random field spin chains

Jisha C[1], Shivam Mishra[2], Ravi Prakash[3]

[1,2,3]Department of Physics, Motilal Nehru National Institute of Technology Allahabad - Prayagraj-211004, India

Out-of-time-ordered correlators (OTOCs) have emerged as a diagnostic of information scrambling and quantum chaos in quantum many-body systems. We investigate the imprints of chaos in the dynamics of OTOCs in the Heisenberg spin-1/2 chain with random fields. The system is parameterized to exhibit a crossover from integrable to chaotic dynamics. The crossovers are observed with the help of both short-range and long-range spectral statistics such as nearest neighbor spacing distribution and number variance. Our studies on OTOC focuses on three distinct dynamical regimes: scrambling, relaxation, and saturation. We systematically examine the behavior of the OTOC in each regime for both local and non-local observables. We demonstrate that the relaxation regime carries signatures of the underlying spectral fluctuations of the system and is useful to distinguish between integrable and chaotic systems. We find that the relaxation rates are approximately the same for both local and non-local observables but depends sensitively on the different realizations of random field. We also study the saturation regime of the OTOC under the framework of the Eigenstate thermalization hypothesis (ETH).

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Synchronization of Stuart-Landau Oscillators by Adaptive Coupling

Jubin George Mathew[1*], Prof. G Ambika[1]

[1]IISER Thiruvananthapuram - 695551, India

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 a local adaptive coupling with decay defined by an adaptation strength(α), a time scale mismatch parameter(ϵ) and coupling strength(K) on coupled Stuart Landau oscillators. We study how this system transitions to synchronization on different network structures, including random, scale free,small world and ring topologies.We report a universal pattern observed in the critical coupling needed for the system for transition to synchronization.

Reviving Coherence and Time Crystals with Nonreciprocal Coupling

K. Karthiga[1], D. V. Senthilkumar [1a] and V. K. Chandrasekar[1]

[1]Centre for Nonlinear Science & Engineering, School of Electrical & Electronics Engineering, SASTRA Deemed University, Thanjavur-613401, Tamil Nadu, India

[1a]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram-695551, Kerala, India

The interplay between coherence, dissipation, and nonreciprocal interactions plays a crucial role in engineering novel dynamical phases of open quantum systems. Here, we consider two collective spin ensembles, each coupled to its own driven-dissipative bosonic mode, and interacting via a common dissipative bosonic field. By introducing nonreciprocity through asymmetric couplings to the shared field, we demonstrate that quantum coherence can be revived from fully decohered states. This revival signals a transition from a time-translational symmetric phase to a spontaneously time-translation symmetry-broken phase, realizing a continuous time crystal. Remarkably, steady-state entanglement emerges even in regions where macroscopic coherence is absent, underscoring the nontrivial impact of engineered dissipation. The phase transitions are characterized using numerical simulations of the full quantum master equation, mean-field analysis in the thermodynamic limit, and Liouvillian spectral properties. Our work provides a robust framework to realize coherence enhancement, steady-state entanglement, and time-crystalline behavior in driven-dissipative quantum systems.

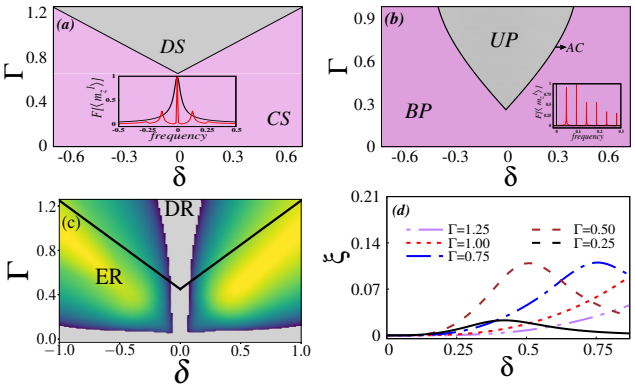

Figure 1: Nonreciprocal control of coherence, time-crystalline phases, and entanglement. Phase diagrams in (δ, Γ) showing the transition from decoherent to coherent oscillatory regimes and the emergence of symmetry-broken (time-crystalline) phases. Nonreciprocity enhances steady-state entanglement and correlates coherence with quantum correlations.

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Probing quasi-geostrophic turbulence via complex networks

V. R. Krishna Priya[1], Snehal Sunil Patil[2], Somnath Roy[2], Konduri Aditya[3], Rajaram Lakkaraju[1,2]

[1]Centre for Computational and Data Sciences and
[2]TuRbulent Interfaces And Dispersion (TRIAD), Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal-721302, India
[3] Department of Computational and Data Sciences, Indian Institute of Science, Bangalore-560012, India

Observations indicate that properties of oceanic eddies such as their number, radius, and lifetime varies with latitude. One of the reasons for these observations is the dramatic variation of Rossby deformation wavenumber with latitude The simplest model to study such large-scale structures in planetary atmosphere and oceans is the two-dimensional Quasi-Geostrophic turbulence given by [1],

$$q_t + \mathcal{J}(\psi, q) = D, \tag{1}$$

where q is the potential vorticity, ψ is the streamfunction, λ is the Rossby deformation wavenumber, D is the energy dissipation and $\mathcal{J}$ is the Jacobian operator. For the barotropic ocean, $\lambda = f/\sqrt{gH}$ where f is the Coriolis parameter, g is the gravitational acceleration, and H is water depth. The Rossby radius wavenumber, λ delineates whether gravity or planetary rotation is the dominant force in stabilizing flow dynamics near the surface. Specifically, when λ is very large, planetary rotation dictates the dynamics to maintain free surface height anomalies, while a reversal indicates relative tendencies of gravity to relax the free surface.

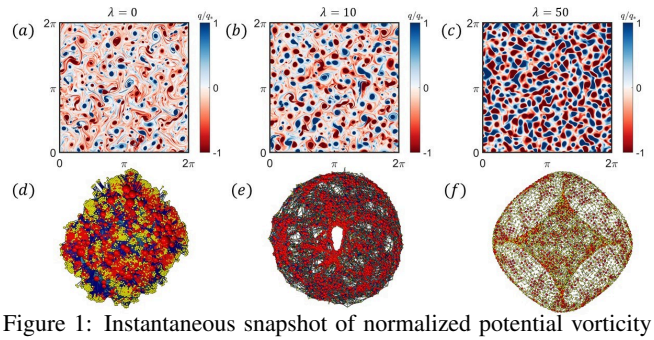

Figure 1: Instantaneous snapshot of normalized potential vorticity (q/q_*) at time $t = 200\tau_0$ for: (a) $\lambda = 0$, (b) $\lambda = 10$, and (c) $\lambda = 50$. Here τ_0 is the eddy turn over time. Turbulent networks of potential vorticity for the above fields, i.e, (d) $\lambda = 0$, (e) $\lambda = 10$, and (f) $\lambda = 50$. The network is constructed from 4096 nodes (low-pass filtered) information of 2048×2048 DNS simulation. Vortical interactions regarding links (lines) and nodes (circles) whose size and color represent strength. Dark red circles are hub nodes, yellow circles are secondary nodes.

Using statistical analysis and complex networks, we study the role of inverse Rossby deformation radius, λ, on freely decaying quasi-geostrophic turbulence dynamics [2]. We find that the area fraction occupied by vortices remains constant over an extended duration for all values of λ. We establish an energy spectrum scaling based on a self-similar distribution of vortices of area A during this period. Our findings suggest that the vortex number density follows the relationship $n(A) \sim N_v A^{-p}$, and the inertial range energy spectra scales as k^{-7+2p}, where N_v represents the number of vortices, and p depends on λ. To investigate vortical interactions, we construct a spatio-temporal weighted network. Our analysis uncovers two distinct strength distributions: (1) a briefly observed scale-free distribution resulting from non-local interactions when $\lambda \ll k_0$, and (2) a truncated scale-free distribution due to local interactions over an extended period when $\lambda \gg k_0$, where k_0 denotes the initial characteristic wavenumber at which the total energy is at its maximum. Both networks are robust against random disturbances but are vulnerable to targeted attacks on their hubs. Additionally, we found that these network hubs contribute to the large-scale energy spectra, which can be reconstructed using only 1% of the total degrees of freedom in a quasi-geostrophic turbulent field. Thus, the network analysis extends the information obtained from classical statistics and offers a deeper understanding of vortex interactions concealed in a quasi-geostrophic turbulence data.

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Gradient, coupling & noise spatio-temporal population dynamics in heterogeneous habitats

Kalyani Murali[1,2], Sitabhra Sinha[1,2]

[1]The Institute of Mathematical Sciences, Chennai, India
[2]Homi Bhabha National Institute, Anushakti Nagar, Mumbai, India

While the time-evolution of populations in a habitat under well-mixed (i.e., homogeneous) conditions is relatively well-understood, in reality, a species population is often spread across space with the resources available to individuals varying from region to region. In addition, the population is subject to temporal fluctuations in the environment, e.g., in terms of reproduction rate. Here we consider a model that exhibits a transition from refuge state (characterized by low population relative to the carrying capacity) to an outbreak state (viz., high population) in the well-mixed situation.

By introducing a gradient in one of the key parameters governing the population growth, we investigate the role played by heterogeneity of the habitat. Fluctuations, e.g., in the form of temporal variation in the carrying capacity faced by the population, also affects the asymptotic state in various locations. Migration of the population from higher to lower density neighbouring regions is incorporated by diffusive coupling. Here, we report the effect of these realistic features on the spatial profile of the population, particularly with reference to the transition from refuge to outbreak states.

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Rate and Noise-Induced Tipping Working in Concert

Keshav Kothari[1]

[1]Department of Data Science, IISER Pune, India

A dynamical system is defined by a set of coupled ordinary differential equations (ODEs) of the form $\dot{x} = f(x)$, where x represents the state vector. Tipping characterizes the phenomenon in which the system's trajectory undergoes a transition from one attractor to another following the variation of specific governing parameters. This process holds profound physical significance, as it provides a framework for modeling abrupt, nonlinear shifts in systemic behavior between distinct stable states.

As described by Lenton et al. (2008), the Earth's climate system contains various "tipping elements"—large-scale components that could pass a critical threshold, leading to significant and potentially irreversible changes in the global environment. Understanding these transitions is vital for predicting the long-term stability of climate subsystems under anthropogenic forcing.

In the context of rate-induced tipping, the governing differential equation incorporates a time-dependent parameter $y(t)$, such that $\dot{x} = f(y(t), x)$. The evolution of this parameter is defined by $\dot{y} = r \cdot g(t)$, where the dynamics are modulated by a constant rate parameter r. Critical transitions between attractors are observed as the magnitude of r varies, forcing the system's trajectory to shift from its initial stable state. In the case of noise-induced tipping, Gaussian noise is incorporated into the dynamical system, with the noise intensity governed by the parameter ϵ. Variations in ϵ facilitate stochastic tipping, driving the system from its primary stable state to an alternative equilibrium.

In this study, we elucidate the synergistic effects of rate and noise, demonstrating that their concurrent action can facilitate tipping at lower thresholds than either mechanism acting in isolation. We substantiate this interaction by analyzing a tractable, two-dimensional dynamical system based on the model proposed by Slyman and Jones (2023), characterized by the following coupled equations:

$$dx = ((x + y)^2 - 1)dt + \epsilon dW_t \tag{1}$$

$$dy = ry(3 - y)dt \tag{2}$$

This model is exactly solvable (when $\epsilon = 0$) and we demonstrate how it serves as a rigorous framework to quantify the amplifying effect of the rate-induced and noise-induced tipping acting together in a system with combined stochastic and rate-dependent perturbations. Finally, we investigate the extent to which this amplifying effect persists in more complex, high-dimensional models employed in the study of climate phenomena. By extending our analysis to these sophisticated frameworks, we evaluate the broader applicability of coupled rate- and noise-induced tipping within the Earth's climate system.

Acknowledgements

The author would like to thank Amit Apte for his valuable guidance and contributions to this work.

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Network-Based Characterization of Flame Dynamics and Instability in LPG–Air Meso-combustors

Koushik Samanta[a], Somnath De[b,*], Sourav Sarkar[a], Achintya Mukhopadhyay[a], Swarnendu Sen[a]

[a]Department of Mechanical Engineering, Jadavpur University, Jadavpur, Kolkata 700032, India
[b]School of Mechanical Engineering (SMEC), Vellore Institute of Technology, Vellore campus, Tamil Nadu 632014, India
[*]Corresponding author: somnath.de@vit.ac.in

Combustion instabilities such as flashback and lean blowout (LBO) pose significant challenges to the stable operation of meso-combustors. Understanding the underlying nonlinear flame dynamics and identifying reliable precursors to instability remain critical. Nonlinear time-series analysis [1], particularly recurrence-based methods, has been used to characterize flame dynamics and detect transitions to combustion instabilities such as lean blowout [2, 3].

In this study, experiments are conducted on a meso-scale combustor for three different duct diameters under premixed LPG–air conditions. Acoustic emissions from the combustor are recorded using a microphone across different flame regimes, including stable (confined) flame, oscillating flame near LBO, and flashback conditions. The acquired acoustic time-series are transformed into complex networks using the visibility graph method [4], enabling analysis of the underlying dynamics through network topology. Murugesan et al. demonstrated that such network representations can capture topological transitions associated with thermoacoustic instability [5]. In the visibility graph method, each data point in the time series is treated as a node. Two nodes i and j are connected if a straight line joining them does not intersect any intermediate data point.

This condition requires that for any intermediate point k such that $i < k < j$, the following must hold:

$$A_{ij} = \begin{cases} 1, & \text{if } x_k < x_i + (x_j - x_i) \\ & \quad \times \dfrac{t_k - t_i}{t_j - t_i}, \quad \forall k \in (i, j), \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Here, A_{ij} represents the adjacency matrix of the visibility graph, where a value of 1 indicates a connection between nodes i and j, and 0 indicates no connection.

Equation (1) ensures that the line joining nodes i and j remains above all intermediate points, thereby preserving the geometric visibility criterion.

The stable confined flame regime is observed at intermediate equivalence ratios, whereas flashback occurs at higher equivalence ratios and oscillating flame behavior is observed near lean conditions approaching LBO. The resulting networks are characterized using degree distribution and global network measures. A key observation is that during flashback and oscillatory flame regimes, the visibility graph exhibits *scale-free behavior*, characterized by heavy-tailed degree distributions. In contrast, the stable flame regime does not exhibit scale-free characteristics. This transition from non-scale-free to scale-free topology reflects a fundamental change in the underlying flame dynamics as the system approaches instability.

The visibility graph networks (Figure 1) constructed from acoustic signals show distinct structural characteristics across different flame regimes. For the flashback regime ($\phi = 1.2$), the network exhibits prominent hub nodes (indicated by red-colored nodes), along with dense connectivity and long-range links. This suggests strong global interactions and highly correlated flame dynamics. In the stable flame regime ($\phi = 0.80$), the network appears more homogeneous with distributed connectivity and absence of dominant hubs. The structure is comparatively less dense and more uniform, indicating regular dynamics. As the equivalence ratio is reduced toward lean conditions ($\phi = 0.70$), the flame transitions to an oscillatory regime close to LBO. In this case, hub nodes begin to reappear; however, they are fewer and less dominant compared to the flashback regime. The network exhibits clustered and fragmented structures, indicating intermittent and transitional dynamics.

Figure 2 shows the variation of normalized network metrics with equivalence ratio. In the oscillating flame regime near LBO ($\phi \approx 0.70$–0.77), relatively high clustering coefficient and modularity are observed, indicating strong local correlations and coexistence of multiple dynamical states. This behavior is characteristic of intermittency preceding instability. In the stable flame regime ($\phi \approx 0.80$–0.90), both graph density and average degree attain minimum values, indicating a sparsely connected network. The absence of hubs and reduced connectivity confirm stable and less complex flame dynamics. As the system transitions to flashback ($\phi \geq 1.0$), a sharp increase in graph density and average degree is observed. The higher values of network metrics, along with the emergence of scale-free charac-

teristics, indicate increasing dynamical complexity and strong global coupling in this regime. It is also observed that at $\phi = 0.80$, although the flame appears visually stable, the relatively higher clustering coefficient compared to $\phi = 0.90$ suggests that this condition may lie close to the onset of instability toward lean blowout. Similarly, at $\phi = 1.1$, a slight reduction in network metrics compared to $\phi = 1.2$ indicates a relative shift of behavior within the flashback regime.

Overall, the results demonstrate a clear topological transition from non-scale-free networks in stable combustion to scale-free, highly connected networks in unstable regimes such as flashback and oscillating flame conditions. This transition reflects a fundamental shift in the underlying nonlinear flame dynamics.

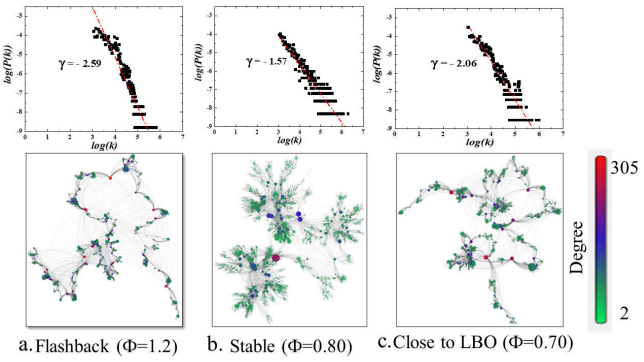

Figure 1: Visibility graphs constructed from acoustic signals for different flame regimes: a. flashback ($\phi = 1.2$),b. stable ($\phi = 0.80$), and c. near LBO ($\phi = 0.70$). Node color represents degree, highlighting the presence of hubs in unstable regimes.

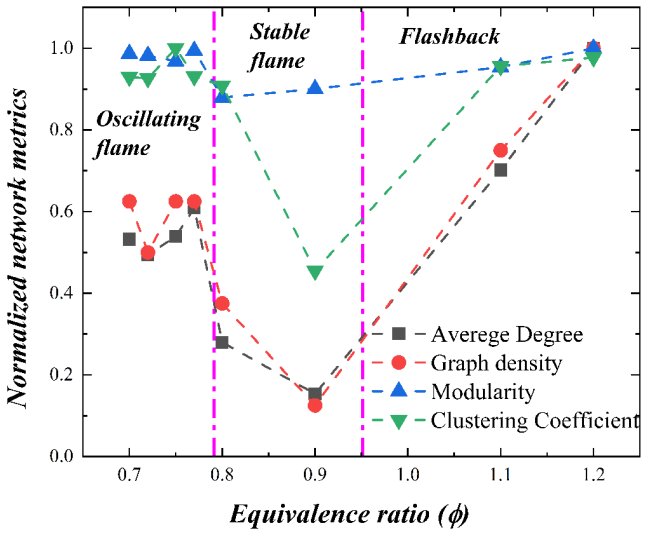

Figure 2: Variation of normalized global network metrics (average degree, graph density, modularity, and clustering coefficient) with equivalence ratio across different flame regimes.

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Modelling Disease Spread in Heterogenous Landscape

Kumar Onker[1], Somdatta Sinha[2]

[1]5th year MS Student, Indian Institute of Science Education and Research Mohali, India
[2] INSA Senior Scientist, Indian Institute of Science Education and Research Kolkata, India

Spread of infectious disease through interconnected subpopulations (metapopulation) can be modelled using the percolation phenomena. In this study, two simple models of evolution of infectious diseases - (a) the generic discrete Host-Parasite (HP) model (Ref1), and (b) the basic malaria model, Ross model (Ref2), are considered, and the infection spread is analysed in landscapes with different patterns of connectivity.

First, the dynamics of both the HP and Ross models are studied in single populations, and the different dynamical states are elaborated analytically and numerically. The metapopulation is modelled using the Coupled Map Lattice (CML) framework (Ref3), where each lattice site is a subpopulation in which the infection evolves following the model equations, and migration among them is diffusive. We study the *percolation time*, defined as the time required for infection to spread from a local region to the entire system, through the diffusion of the infected individuals to nearest-neighbour subpopulations in the lattice. Heterogeneity in the lattice landscape is introduced through the presence of vacant sites, leading to irregular transmission networks across the system, thereby influencing the percolation of infection across the metapopulation.

The discrete HP model exhibits an array of dynamics from stable, oscillatory, quasi-periodic and chaotic. The Ross model provides a fundamental framework for describing malaria transmission between the susceptible and infected humans and mosquitoes under homogeneous mixing assumptions. It shows only stable dynamics under different parameter variations.

In the metapopulation scenario, we first investigate the spatiotemporal dynamics of infection spread in the two models under homogeneous condition, i.e., when all sites are occupied and have the same nearest-neighbour connectivity for migration in a closed boundary (island-type) landscape. We find the percolation time in different configurations. Different types of structural heterogeneity - random and patterned - are introduced in the landscape, and the percolation times and their distributions are compared between homogeneous and heterogeneous configurations. Our results indicate that such structural heterogeneity can significantly influence disease propagation with disrupted connectivity, generally increasing percolation time. These findings highlight the role of spatial structures (cordoning, lockdown, vaccination, etc.) in shaping epidemic dynamics in different types of disease evolution models.

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Collective Dynamics in Networks of Bistable Stuart–Landau Oscillators

Kumar Sourav[1], **Thounaojam Umeshkanta Singh**[1]

[1]Bennett University, Uttar Pradesh, India

Diffusively coupled networks of Stuart–Landau oscillators exhibit rich collective dynamics, including disorder–order transitions and synchronization phenomena. In our previous work [1], we demonstrated abrupt transitions to synchronized states accompanied by frequency flips in large ensembles ($N = 1000$) of oscillators coupled on directed ring networks [1, 2, 3]. In this study [4], we extend the analysis to a modified Stuart–Landau model with a shifted nonlinear amplitude term, which introduces intrinsic bi-stability through the coexistence of stable and unstable limit cycles. We investigate the collective dynamics of large oscillator ensembles under both unidirectional and bidirectional coupling schemes. The presence of intrinsic bistability leads to pronounced multistability at the network level, resulting in strong dependence on initial conditions and nontrivial basin structures. Numerical simulations reveal the emergence of amplitude death, partial synchronization, and re-entrant oscillatory behavior as the coupling strength is varied. We find that the transition to amplitude death is governed not only by coupling strength but also by the distribution of initial amplitudes, reflecting the underlying basin geometry of the system. These results highlight the crucial role of intrinsic nonlinear structure and multi-stability in shaping collective behavior in large networks of non-isochronous oscillators, extending earlier findings on synchronization transitions in Stuart–Landau systems.

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Ensemble-Based Forecasting and Koopman Spectral Characterization of $PM_{2.5}$ Dynamics in Delhi

Lakshmi Manalipadam[1], Charu Sharma[1]

[1]Department of Mathematics, Shiv Nadar Institute of Eminence, Greater Noida, UP, India, 201314

Understanding and forecasting urban air pollution remains challenging due to its nonlinear, non-stationary, and spatiotemporally evolving nature.This study investigates the dynamics of $PM_{2.5}$ concentrations across 16 monitoring stations in Delhi using Dynamic Mode Decomposition(DMD) to uncover the underlying dynamical structures governing pollution variability.A sliding window technique is used to evaluate hourly $PM_{2.5}$ observations obtained from Central Pollution Control Board(CPCB) to capture evolving temporal dynamics.We examine several DMD variants, including standard DMD, Optimized DMD(OptDMD), Bagging Optimized DMD(BOPDMD), and Hankel DMD.

Forecasting is performed using an ensemble averaging strategy across overlapping sliding windows to increase robustness and lower the prediction variance. Model performance is evaluated using normalized root mean square error (NRMSE), calculated with respect to both the standard deviation and the range, along with mean absolute percentage error (MAPE). Additionally, forecast horizon-wise error analysis is conducted to assess the degradation in predictive accuracy with increasing lead times.

Results indicate that Hankel Dynamic Mode Decomposition (Hankel DMD) consistently outperforms standard DMD, Optimized DMD (OptDMD), and Bagging Optimized DMD (BOPDMD) across monitoring stations, achieving the relatively lowest forecasting errors with NRMSE (standard deviation) of approximately 50%, NRMSE (range) of approximately 6%, and MAPE of approximately 42%. The increase in the prediction accuracy can be attributed to delay embedding which better captures intrinsic temporal dependencies, thereby enhancing the approximation of the underlying linear Koopman dynamics.

Further analysis of Koopman eigenvalues obtained from the sliding window framework shows a clear temporal variations, indicating transitions between different dynamical regimes. These regime shifts are related to changes in pollution intensity and atmospheric conditions, highlighting the capability of the proposed framework to not only provide accurate short-term forecasts but also offer insights into the evolving dynamical structure of urban air pollution.

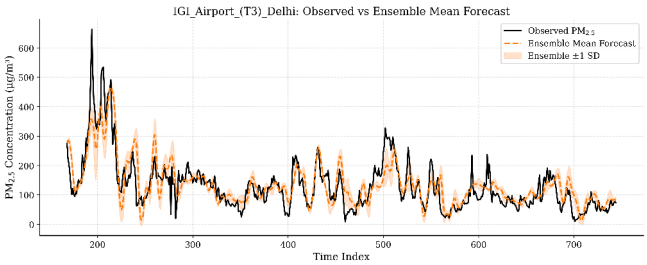

Figure 1: Observed and forecasted PM2.5 for a particular station(IGI Airport) for January month.

Overall, this study highlights the potential of Hankel DMD as an effective framework for spatiotemporal air pollution forecasting and dynamical interpretation.The integration of ensemble forecasting with eigenvalue-based regime analysis provides a unified approach for both prediction and structural understanding of environmental systems, with potential applications in real-time air quality monitoring and early warning systems

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Interaction of Airy beams in nonlocal nonlinear medium

Mamatha K L[1],Stalin S[2], Nithyanandan K[1]

[1]Ultrafast Fiber Optics & Smart Photonic Technologies Lab, Department of Physics, IIT Hyderabad
[2]Department of Physics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India

In recent years, nonlocal nonlinear optical media have attracted significant research interest due to their unique physical characteristics. In such media, the change in refractive index at a given point depends not only on the local light intensity but also on the intensity distribution in the surrounding region, leading to long-range interactions and enhanced beam stability. Despite considerable progress, the interaction dynamics of Airy beams in nonlocal nonlinear media with competing nonlinearities remain largely unexplored.

In this work, we study the interaction of Airy beams in a nonlocal nonlinear medium with competing self-focusing and self-defocusing nonlinearities arising from reorientational and thermal effects. The system is modeled using the nonlocal nonlinear Schrödinger equation (NNLSE).

$$i\psi_z + \tfrac{1}{2}\psi_{xx} + \psi\left[1 - \gamma\int R_2(x-\xi)|\psi(\xi,z)|^2 d\xi\right] \times \int R_1(x-\eta)|\psi(\eta,z)|^2 d\eta = 0 \tag{1}$$

Here, γ is the thermal nonlinearity coefficient. The nonlocal response functions are assumed to follow Gaussian distributions, and is given by

$$R_{1,2} = \frac{1}{\sqrt{\pi}\,\sigma_{1,2}}\exp\left(-\frac{x^2}{\sigma_{1,2}^2}\right). \tag{2}$$

Where, $\sigma_{1,2}$ width of the response function. The initial field profile is taken as a superposition of two finite-energy Airy beams with a controllable phase difference, expressed as

$$\psi = A\left[\mathrm{Ai}(x-B)e^{a(x-B)} + e^{i\pi\rho}\mathrm{Ai}(-x+B)e^{-a(x+B)}\right]. \tag{3}$$

Here, A is amplitude, B is beam intervals, Ai represents Airy beams, $\rho = 0$ and $\rho = 1$ indicates the in-phase and out-off-phase Airy beams, and $a > 0$ is the decaying factor. The governing equation is solved numerically using the split-step Fourier transform method to analyse the interaction behaviour of Airy beams. We investigate the interaction dynamics of Airy beams under two distinct conditions: (i) gradual variation of the nonlocality and (ii) abrupt changes in the nonlocality. Such variations can be achieved by controlling the applied voltage in nematic liquid crystals. The corresponding results are presented in Figs. 1 and 2, respectively.From the figures, it is observed that in the in-phase case, the beams attract each other up to a separation distance of $B = 4$, beyond which they propagate nearly parallel. In contrast, out-of-phase beams exhibit consistent repulsion during propagation. The interaction dynamics are strongly influenced by the nature of nonlocality: gradual variations lead to smooth and controlled evolution, whereas abrupt changes result in stronger, more localized but less stable interactions.

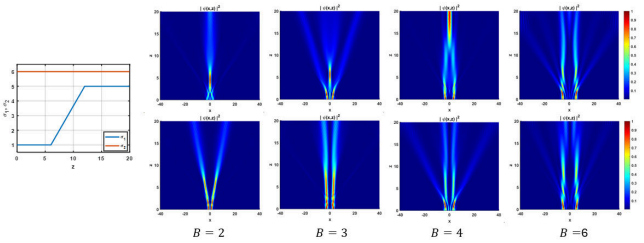

Figure 1: In-phase(first row) and out-of-phase(second row) interaction of airy beams in the case of the gradual changes in the nonlocality

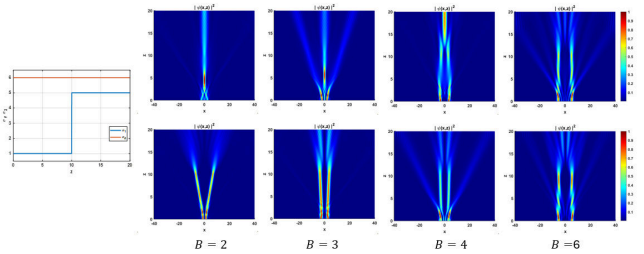

Figure 2: Similar to fig. 1, but for the abrupt changes in the nonlocality

These results demonstrate that controlled variations in the nonlocal response can significantly modify beam interactions, leading to rich propagation dynamics. This highlights the potential of tailoring nonlocality for precise control of optical beam interactions, with promising applications in all-optical interconnections and advanced photonic devices.

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Degenerate and Mixed Soliton Dynamics: Analytical Study and Machine Learning Prediction in Coupled Higher-Order Nonlinear Schrödinger equations

S. Monisha[1], **K. Nithyanandan** [1]

[1] Department of Physics, Indian Institute of Technology Hyderabad, Telangana, India.

This study investigates the mathematical formulation, asymptotic behavior and approximation of degenerate soliton (DS) and mixed soliton solutions within a coupled higher-order nonlinear Schrödinger (CHNLS) system. Such systems are critical for modeling femtosecond optical pulses and wave propagation in complex media like elliptically birefringent fibers, where higher-order nonlinear effects significantly influence pulse dynamics. We utilize the generalized Darboux transformation (DT) method to construct three distinct classes of degenerate solutions: one set on a plane wave background and two on a zero background. By imposing specific degeneracy conditions on the spectral parameters within the Lax pair formulation, we derive exact analytical expressions for higher order DS solutions. The study further extends this methodology to generate hybrid structures, including interactions between second-order DS and single or multiple solitons. A key contribution of this work is the systematic investigation into how the higher-order nonlinear parameter (α) modulates wave geometry, results in a significant spatial compression of localized structures, causing wave humps to merge into more intense unified peaks. The spatial separation between asymptotic profiles grows logarithmically as α increases. Collisions between DS and fundamental solitons are shown to be elastic, with wave structures recovering their original profiles and amplitudes after interaction. Through asymptotic analysis, the study confirms that in the far-field limit ($t \to \pm\infty$), a second-order DS effectively decomposes into two independent soliton-like entities [1].

To bridge analytical theory with numerical approximation, we employ Physics Informed Neural Networks (PINNs). By embedding the governing CHNLS equations directly into the neural network's loss function, the PINN framework predicts DS solutions with high precision. Unlike traditional methods, this approach utilizes data at a single spatial location ($x = 0$) and the initial condition ($t = 0$), achieving a mean squared error at the 10^{-6} level [2]. The findings offer deep theoretical insights into degenerate soliton interactions and confirm the robustness of hybrid solutions against variations in nonlinearity. These results provide valuable guidance for practical applications in optical fiber communications, fluid dynamical systems, and the design of materials for wave-energy manipulation.

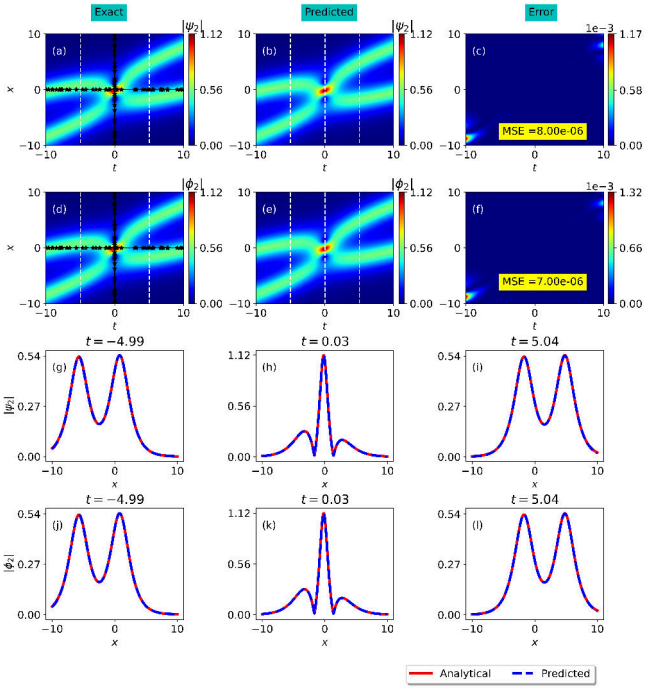

Figure 1: Comparison of analytical and PINN predicted results of the second-order DS solutions for the two components ψ_2 and ϕ_2.

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Frustration-Induced Multistability in Non-Reciprocal Kuramoto Networks

Mythilipriya A[1], Chandrasekar V K[1], Senthilkumar D V [2]

[1]Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering,SASTRA Deemed University, Thanjavur 613 401, India

[2]School of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram 695551, Kerala, India

We investigate the collective dynamics of a two-population Kuramoto model with non-reciprocal interactions and finite phase lag. Asymmetric coupling between the populations breaks action–reaction symmetry and drives the system out of equilibrium.

Using numerical simulations together with a reduced mean-field description, we analyze the system behavior across the parameter space. The interplay between non-reciprocity and phase lag introduces frustration, leading to a variety of dynamical states, including coherent phase-locked states, π-states, oscillatory regimes, and travelling wave solutions.

We identify regions of multistability where different dynamical states coexist. These regions are organized by saddle-node and Hopf bifurcations, resulting in bistability between steady and time-dependent states. This is further confirmed by hysteresis observed under forward and backward parameter sweeps.

Non-reciprocal coupling also leads to asymmetry between the two populations, producing distinct macroscopic behaviors even with identical intra-population interactions. Phase lag enhances this effect and facilitates transitions between competing states.

Overall, our results show that non-reciprocity and phase lag significantly modify synchronization and lead to complex nonequilibrium dynamics in coupled oscillator systems, with relevance to real-world networks such as neuronal systems, power grids, and active matter.

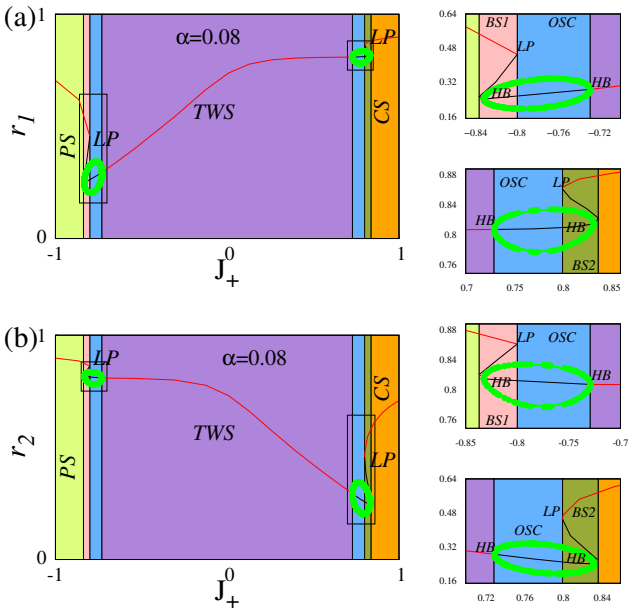

Figure 1: Phase diagram of the two-population Kuramoto model with non-reciprocal coupling and phase lag α, showing different dynamical states as a function of J_+. Regions correspond to coherent (CS), π-state (PS), oscillatory (OSC), travelling wave (TWS) states and Bistable states.

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Collective Synchronization in Optomechanical Systems

M. Ashiha Nazeera[1], R. Gopal[1] and V. K. Chandrasekar[1]

[1]Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613 401, India

Optomechanics provides a powerful platform for exploring the interplay between light and mechanical motion via radiation-pressure coupling in optical cavities. By linking microscopic optical fields with macroscopic mechanical resonators, these systems naturally exhibit intrinsic nonlinear behavior and serve as an ideal testbed for studying complex dynamical phenomena. The dynamics of such systems can be described by the master equation.

$$\frac{d\rho}{dt} = -i[H, \rho] + \mathcal{L}_m\rho + \mathcal{L}_c\rho$$

which accounts for both the coherent evolution governed by the system Hamiltonian H and the dissipative processes associated with the mechanical and optical degrees of freedom.

When extended to coupled arrays, the interplay of mechanical coupling, tunable laser detuning, and dissipation leads to a wide range of dynamical regimes, from independent oscillations to coherent collective motion. These systems offer a unique framework to understand how synchronization emerges in driven, dissipative nonlinear environments. Despite significant progress, a comprehensive understanding of how collective synchronization arises in extended optomechanical lattices, particularly beyond linearized models and across different dynamical regimes, remains an open challenge.

Here, we investigate the fundamental mechanisms governing phase and frequency locking in optomechanical lattices, with particular emphasis on how key system parameters influence the onset of coordinated behavior. We further analyze the global stability of coupled optomechanical systems and explore the emergence of collective dynamics as a function of coupling strength, detuning, and dissipation.

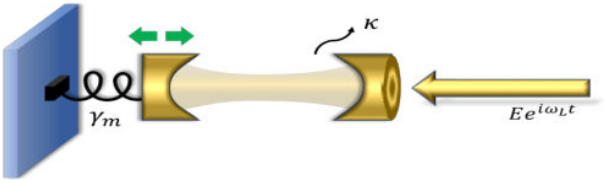

Figure 1: Schematics of an optomechanical system.

We seek to identify parameter regimes that support synchronization. We also examine nonlinear phase dynamics. Our goal is to understand the transition from classical phase-locking to quantum synchronization in dissipative cavities.

These insights deepen the understanding of nonlinear many-body dynamics. They also have implications for realizing coherent phononic networks, high-precision sensing architectures, and quantum technologies based on controlled collective behavior.

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Soliton Propagation in Helimagnetic Spin Systems

M.P. Joselin, E. Parasuraman*

Department of Physics, Vellore Institute of Technology, Chennai Campus, Tamil Nadu 600 127, India

Helimagnets are a class of magnetic materials in which atomic spins form a helical structure due to competing exchange interactions and spin-orbit coupling [1]. These materials have attracted significant interest for their potential applications in spintronics, quantum computing, and high-density data storage. The spin dynamics in helimagnets is commonly described by the Landau-Lifshitz equation, mostly coupled with Maxwell's equations [2]. When these equations are studied under suitable approximations, they reduce to nonlinear Schrödinger (NLS) equation and their extensions. One particular relevant extension is the generalized NLS equation, which incorporates higher-order effects such as nonlinear dispersion, self-steepening, and helicity-driven interactions [1].

We consider a generalized fourth-order NLS equation governing spin dynamics in an anisotropic helimagnetic system. The completely integrable form exists only under specific parametric conditions, whereas the present model is non-integrable and exhibits complex nonlinear behavior[3]. To analyze the complex nonlinear behavior of this non-integrable model, the New Extended Auxiliary Equation Method (NEAM) is employed, which enables the construction of exact analytical solutions for various wave structures. By applying an appropriate travelling wave transformation, the governing partial differential equation is reduced to an ordinary differential equation, which is then solved using the NEAM framework [4]. Various classes of solutions, including solitary wave and periodic wave structures, are obtained for different parametric regimes. The obtained results provide deeper insight into spin wave dynamics and offer a systematic approach for controlling nonlinear excitations in helimagnets by knowing the nature of the solitons formed. This is essential for the development of next-generation magneto-electric devices and high-performance spintronic applications.

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Noise induced intermittency and strange attractor in electronic Lorenz oscillator

Madhusmita Panda[1], Mantra Bhatnagar[2], Kumar Sourav[1], Thounaojam Umeshkanta Singh[1]

[1]Department of Physics, School of Engineering and Applied Science, Bennett University, Greater Noida, Uttar Pradesh, India
[2]Department of Electronics and Communication Engineering, School of Engineering and Applied Science, Bennett University, Greater Noida, Uttar Pradesh, India

Noise is ubiquitous in natural and engineered systems and, in nonlinear dynamics, acts not merely as a perturbation but as a driver of complex behavior, including chaos, order, and instabilities. The Lorenz system, a paradigmatic model, exhibits dynamical regimes ranging from steady states to chaos depending on the control parameter r, identified with the Rayleigh number. While the deterministic system is stable for $r < 1$, with trajectories relaxing to the origin, the addition of external white noise to the z-component can qualitatively transform the dynamics, leading to markedly different behavior [1, 2].

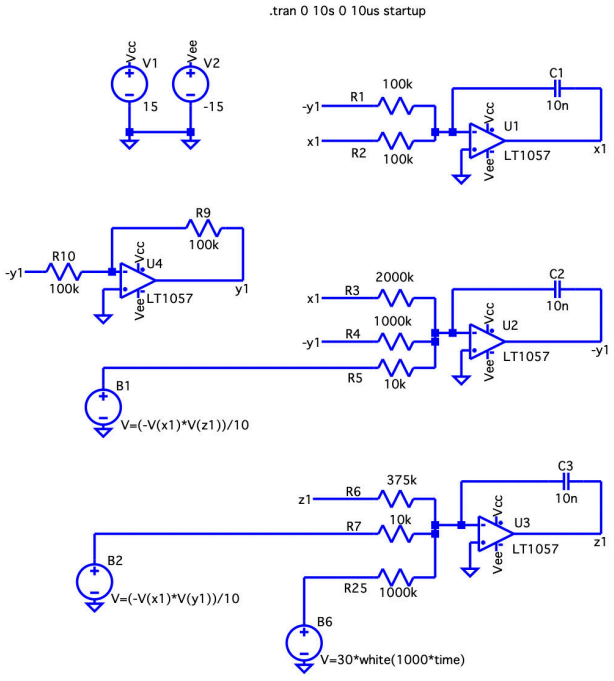
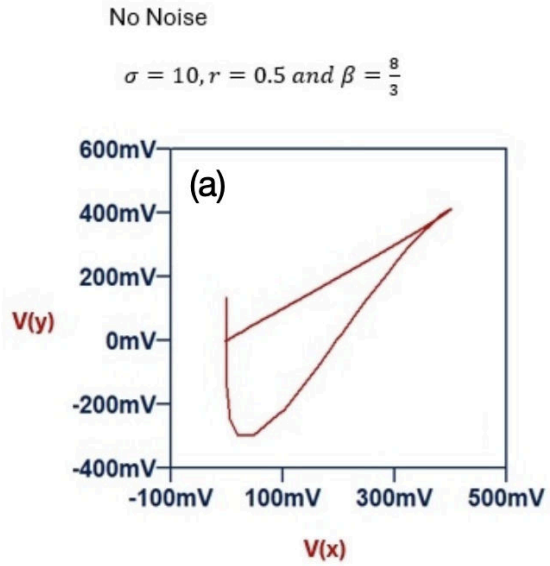


Figure 1: Circuit diagram for investigating noise-induced dynamics in the Lorenz system with additive white noise applied to the z-variable.



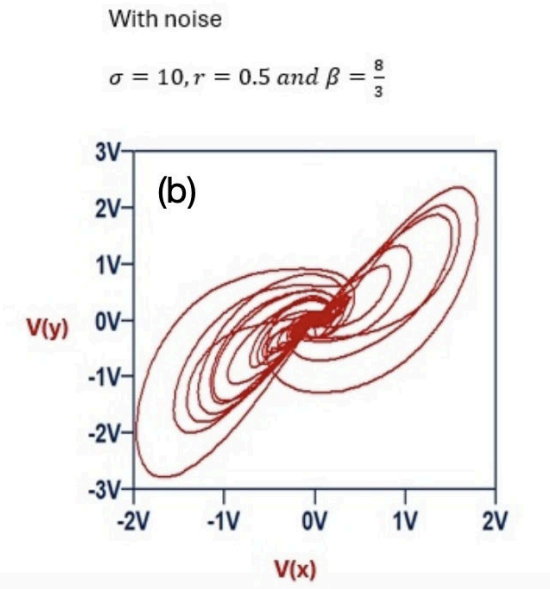


Figure 2: Noise-induced strange attractor in an electronic Lorenz system with additive white noise in the z-variable. (a) In the absence of noise, the system relaxes to a quiescent equilibrium. (b) For sufficiently strong noise, a strange attractor emerges, supporting intermittent dynamics.

Building on this, we implement an electronic circuit realization of the Lorenz system in which additive white noise is injected into the z-variable. The dynamics are

governed by

$$\begin{aligned} \dot{x} &= \sigma(y-x), \\ \dot{y} &= x(r-z)-y, \\ \dot{z} &= -\beta z + xy + \alpha\xi(t), \end{aligned} \tag{1}$$

where $\xi(t)$ denotes Gaussian white noise and α is the strength of the noise intensity, while σ, r, β are real parameters. In the system, $r = 0.5$, $\sigma = 10$ and $\beta = 8/3$, with the noise intensity α varied as the control parameter to probe different dynamical regimes. This framework enables a direct examination of how noise reshapes the underlying Lorenz dynamics. To realize the noise-induced Lorenz system as an electronic circuit [3, 4, 5], the original governing equations are transformed into equivalent circuit-based equations using resistor networks, capacitors, and operational amplifiers shown in Fig. 1.

Within this framework, a striking effect of noise emerges in the nominally stable regime $r < 1$. In the absence of noise, the deterministic system relaxes to a quiescent equilibrium, as shown in Fig. 3(a). However, our circuit experiments [5] reveal that increasing the noise strength drives the system away from this state, inducing sustained intermittent dynamics that give rise to a strange attractor, as illustrated in Fig. 3(b). Thus, noise effectively acts as a control parameter, triggering a transition from a stationary to an active dynamical regime without any change in r [5].

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Learning Control Policies from Data-Driven Models of Non Linear Dynamics

Manasvee Baranwal

Energy Department, IIT Bombay

We investigate whether control policies can be reliably learned from data-driven models of nonlinear dynamical systems. Specifically, we propose a discovery–control pipeline in which governing equations are first identified from time-series data using Sparse Identification of Nonlinear Dynamics (SINDy), and subsequently used to train control policies via reinforcement learning (RL).

Using the FitzHugh–Nagumo (FHN) excitable system as a benchmark, we demonstrate that SINDy accurately recovers the underlying nonlinear dynamics from simulated trajectories. Reinforcement learning is then successfully employed to suppress self-sustained oscillations and steer the system toward a stable regime. However, we show that a naive use of the discovered model for control can fail when control inputs are implicitly absorbed into constant terms during the identification process. This leads to a mismatch between the learned dynamics and the true control structure, resulting in ineffective policies.

To address this, we introduce a control-aware formulation in which input channels are explicitly incorporated into the discovered model. With this modification, RL trained on the identified system achieves performance comparable to that obtained using the true governing equations. We further examine the robustness of the pipeline under measurement noise, highlighting the impact of identification error on downstream control performance.

Our results demonstrate that while data-driven discovery can enable effective control learning, preserving the structural role of control inputs is critical. This work provides a step toward integrating system identification and control in nonlinear dynamical systems using machine learning.

A Neural Network Framework for Nonlinear Flame Describing Function Prediction Using Multi-Frequency Excitation

Souranshu R. Chaudhuri, Manish K. Manna, Sourav Sarkar, Achintya Mukhopadhyay

Jadavpur University, Kolkata, India

Thermoacoustic instabilities arise from the coupling between unsteady heat release and the acoustic field in confined systems, leading to large amplitude oscillations. These instabilities can cause severe vibrations, enhanced heat transfer, and structural damage in gas turbines and rocket engines. Accurate prediction is therefore essential for stable propulsion system design, guiding strategies such as injector configuration, baffle placement, and acoustic damping [1]. In this work, a data-driven framework based on machine learning (ML) is proposed to model and predict the nonlinear thermoacoustic response of a system. Unlike conventional approaches that rely on solving governing equations or performing expensive simulations, the present method learns the functional relationship between velocity perturbations and heat release fluctuations directly from data. The multilayer perceptron (MLP) architect employed in this model is particularly well-suited for capturing complex non-linear relationships without requiring explicit governing equations [2].

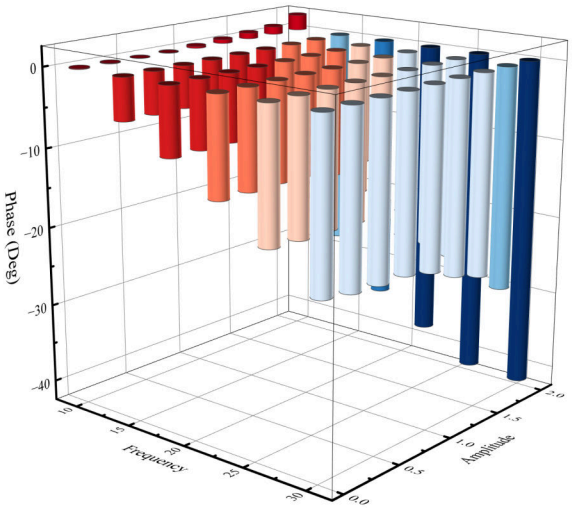

Figure 1: Three-dimensional phase (lag) behaviour of the flame describing function predicted using the trained machine learning model as a function of forcing amplitude and frequency.

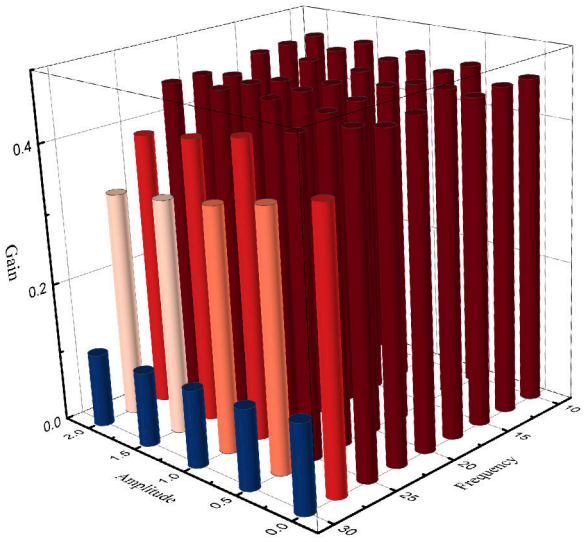

Figure 2: Three-dimensional gain behaviour of the flame describing function predicted using the trained machine learning model over a range of forcing amplitudes and frequencies.

The model is trained using multiple input signals comprising sinusoidal excitations across a range of amplitudes and frequencies, thereby embedding both linear and nonlinear system dynamics into the training process. By exposing the model to diverse excitation conditions, it effectively learns a generalized nonlinear mapping of the form:

$$Q'(t) = f\big(u'(t-\tau)\big)$$

This enables a predictive capabiltiy beyond the training set. The trained model is subsequently used to construct the Flame Describing Function (FDF), which characterizes the system response in terms of gain and phase lag as functions of excitation amplitude and frequency. The resulting 3D gain and phase surfaces provide a comprehensive visualization of the nonlinear flame response.

The phase (lag) change (See Fig. 1) reveals a clear increase in phase lag with increasing amplitude and frequency, indicating the presence of nonlinear time-delay effects in the system. At low amplitudes, the phase remains close to zero, corresponding to a quasi-linear regime. As amplitude increases, the phase shifts become more pronounced (approaching $-40°$), highlighting strong nonlinear interactions between flow perturbations and heat release dynamics. This trend is consistent

with physical expectations in combustion systems where non-linear flame interactions dominate at higher forcing levels.

The gain distribution (see Fig. 2) demonstrates characteristic nonlinear saturation behavior. At low amplitude and low frequency the high gain indicates a strong coupling between flow oscillations and heat release. However, as amplitude increases, the gain begins to plateau and eventually reduce to a much lower value, reflecting the transition from linear amplification to nonlinear saturation. This behavior is a hallmark of flame describing functions and validates the capability of the ML model to capture essential nonlinear physics.

Overall, the results demonstrate that the proposed ML framework can successfully learn and reconstruct the nonlinear thermoacoustic response using only data-driven training on multiple excitation functions. The ability of the model to interpolate across unseen amplitudes and frequencies highlights its potential as a fast, reliable surrogate for thermoacoustic analysis, significantly reducing computational cost compared to traditional methods. This approach opens new avenues for real-time prediction, control, and design optimization of combustion systems.

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Propagation dynamics of Hermite-Gaussian soliton for HNLSE with PT-Symmetric complex potential

Munish[a], **Nisha**[b], **Amit Goyal**[a]

[a]Department of Physics, Goswami Ganesh Dutta Sanatan Dharam College, Chandigarh 160030, India
[b]Department of Physics, Panjab University,Chandigarh 160014,India
manishjattan142gmail.com

In recent times, the scientific community has emphasized a great deal on research related to PT-symmetric non-Hermitian systems. This field evolved following the seminal work in quantum mechanics by **Bender** and **Boettcher** in 1998 [1], which showed that even non-Hermitian Hamiltonians can exhibit entirely real spectra, provided the Hamiltonian obeys PT-symmetry. After being theoretically debated for several years as a purely mathematical development, it was subsequently recognised that optics can provide a fertile ground to realise PT-symmetry by judiciously adjusting the gain/loss of the media. The experimental observation of parity-time symmetry in optics by **Musslimani** et al. in 2008 [2] opened a gateway to explore PT-symmetry in various physical settings such as electronics, BEC, photonics, and atomic systems.

Tracing the developments in nonlinear optics, a stationary Hermite-Gaussian (HG) soliton was obtained for the nonlinear Schrödinger equation (NLSE) with a PT-symmetric complex potential [3]. Extending this work to the higher-order NLSE (HNLSE) with a parity-time symmetric complex potential, we have analytically investigated the existence of Hermite-Gaussian soliton solutions under certain parametric conditions. Furthermore, by employing the iso-spectral deformation of the Hamiltonian, a one-parameter family of complex potentials is generated, which enables modulation of the intensity and symmetry of the HG soliton. These findings could be beneficial for various optical phenomena such as ultrafast photonics.

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Lagrange Synchronization of Higher Dimensional Cohen-Grossberg neural networks with interaction terms and discrete and distributed time delays

Manjari Rastogi[1], Subir Das[1], H. Jafari[2]

[1] Department of Mathematical Sciences, Indian Institute of Technology (BHU), Varanasi, India
[2] Department of Mathematical Sciences, University of South Africa, UNISA-0003, South Africa

This work investigates the Lagrange synchronization problem of nonidentical higher-dimensional neural networks, focusing on Cohen–Grossberg octonion-valued neural networks (CGOVNNs) with interaction terms, as well as discrete and distributed time-varying delays. The analysis of such systems is particularly challenging due to the non-commutative and non-associative properties of octonion algebra, which significantly complicate the mathematical operations and stability analysis compared to real, complex, or even quaternion-valued systems. To address this issue, the octonion-valued neural network is decomposed into eight real-valued subsystems, enabling a systematic and tractable analytical framework. A nonlinear controller is developed to guarantee synchronization, and an appropriate Lyapunov function is constructed. Based on Lyapunov stability theory, sufficient conditions for achieving Lagrange synchronization are derived. Finally, numerical simulations are presented to validate the effectiveness and feasibility of the proposed approach.

Dynamics of a Piecewise Linear (PWL) Hindmarsh-Rose (HR) Neuron Model

Nadhiya K. V.[1], Arif T. A.[1], Ishaq Ahamed A.[2]

[1]Department of Physics, Ansar Women's College, Perumpilavu, Thrissur, India
[2]Department of Physics, Jamal Mohamed College (Autonomous),
Affiliated to Bharathidasan University, Tiruchirappalli, India

This work investigates the intricate dynamics of a modified Hindmarsh-Rose (HR) neuron model which incorporates an active three-segment flux controlled piecewise linear memristor as its nonlinear element [1]. By applying the theory of discontinuous dynamical systems, the firing behaviors and extreme multi-stability of this system are investigated. The system's transition between periodic and chaotic states are captured through bifurcation diagrams and phase portraits.

The verification of chaos in this system has been carried out using Lyapunov exponents and the 0-1 Test (K-test) [2]. Both of these tests effectively distinguish the regular behaviour from chaotic motions, providing robust numerical evidence for the system's complexity. The multi-stability of the system has been investigated numerically using basins of attraction, phase portatis and time plots [3]. The presence of extreme multi-stability may be attributed to the switching-induced bifurcations which lead to the coexistence of multiple spiking and bursting states.

These findings demonstrate that the interaction of the memristive flux at the switching manifolds, significantly enriches the firing diversity of artificial neurons, offering new insights into the modeling of complex neuronal networks.

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Propagation of electromagnetic waves in Parabolic nonlinear Metamaterial

Neha Rajpoot, E. Parasuraman*

Department of Physics, Vellore Institute of Technology, Chennai Campus, Tamil Nadu 600 127, India

The propagation of electromagnetic waves in metamaterials, characterized by their negative refractive index and unique dispersive properties, has attracted significant attention due to their ability to support stable localized structures such as solitons [1]. The complex interaction between dispersion, nonlinearity, and higher-order perturbation effects requires the development of advanced nonlinear models to accurately describe wave dynamics in such media[2]. In particular, nonlinear Schrödinger-type equations incorporating higher-order nonlinearities provide a more realistic framework for analyzing pulse propagation in metamaterials. In the present work, we consider a generalized nonlinear Schrödinger equation with cubic-quintic nonlinearity and higher-order perturbation effects of the form.

$$\begin{aligned} iB_t + \sigma_1 B_{xx} + \sigma_2 \left(|B|^2 B + \sigma_3 |B|^4 B\right) \\ = i\sigma_4 B_x + i\sigma_5 (|B|^2 B)_x \\ + i\sigma_6 (|B|^2)_x B + \sigma_7 |B|^2 B_{xx} \\ + \sigma_7 (|B|^2 B)_{xx} + \sigma_8 B^2 B^*_{xx} \end{aligned} \tag{1}$$

The above equation represents a higher-order nonlinear model that incorporates both cubic and quintic nonlinear effects along with dispersive and perturbative contributions arising in metamaterial structures. The main objective of this work is to analyze the formation and behavior of localized wave structures governed by the interplay of nonlinearity, dispersion, and higher-order perturbations[3]. To facilitate analysis, a traveling wave transformation is employed to reduce the governing nonlinear partial differential equation into an ordinary differential equation. The resulting equation is then solved analytically by applying the New Extended Auxiliary Equation Method (NEAEM)[4]. This method enables the construction of exact solutions in terms of solitary wave and periodic wave structures, providing a systematic approach for handling higher-order nonlinear evolution equations. The obtained results reveal the significant influence of nonlinear and perturbation parameters on the amplitude, width, and stability of the resulting wave structures. The study highlights the effectiveness of NEAEM in analyzing complex nonlinear models and provides deeper insight into soliton dynamics in metamaterials, with potential applications in optical communication systems and photonic device engineering.

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Modulational Instability in Non-Collinear Ferromagnetic Thin Films with Dzyaloshinskii–Moriya Interaction

Neja Prinsa N, E. Parasuraman

Department of Physics, School of Advanced Sciences, Vellore Institute of Technology, Chennai-600127, Tamil Nadu, India

Modulation instability (MI) is one of the most fundamental effects associated with wave propagation in nonlinear dispersive systems [1, 2]. MI plays a pivotal role in the generation and evolution of localized modes in a wide range of ferromagnetic systems [3, 4]. In this work, we study MI in ferromagnetic thin films, explicitly incorporating the effects of both Dzyaloshinskii-Moriya interaction (DMI) and spin canting.

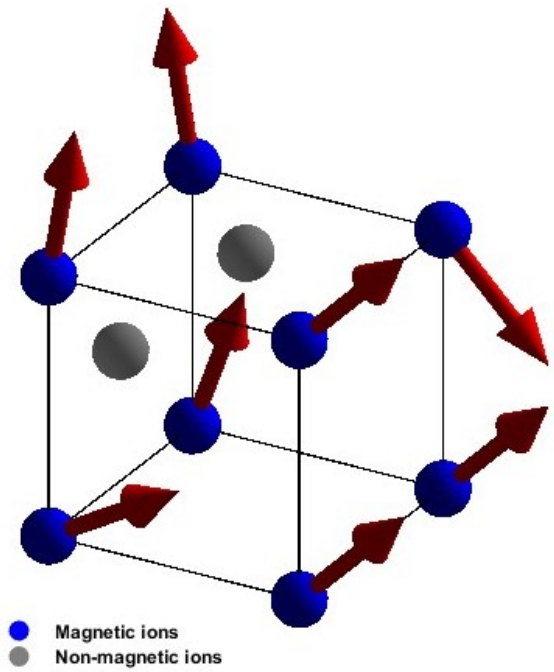

Figure 1: Spin configurations in a simple cubic lattice of a ferromagnetic thin film with non-magnetic ions introduced at selected sites.

The system is modeled as a quasi-discrete Heisenberg spin lattice composed of a simple cubic structure, where magnetic ions are located with non-magnetic ions as shown in Fig. 1. These non-magnetic ions induce DMI between neighboring spins through local inversion symmetry breaking. In the absence of DMI, the system exhibits a uniform collinear ferromagnetic ground state. However, the introduction of DMI leads to a canting of adjacent spins, resulting in a non-collinear spin configuration within the film plane. Incorporating the canting as an effective contribution from the induced DMI, we derive the governing dynamical equations for spin excitations in the semiclassical limit. Using a multiple-scale perturbation approach, the discrete spin system is reduced to a nonlinear Schrödinger (NLS) equation that captures the evolution of spin wave envelopes. The stability of plane wave solutions is analyzed through standard MI analysis. The MI gain spectrum is obtained, and the conditions for the onset of instability are identified in terms of system parameters such as exchange interaction strength, DMI coefficient and canting angle. Our results reveal that the presence of DMI and canting angle significantly modifies the instability regions and enhances the growth rate of perturbations under certain parametric regimes

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Physics-Informed Neural Networks for Dynamic System Identification: Experimental Validation and Identifiability Analysis

Nishant[1], **S. P. Singh**[1]

[1]Indian Institute of Technology, Delhi, India

Accurate identification of dynamic system parameters is important for vibration analysis and design, but traditional methods often face difficulties due to noise, modeling assumptions, and limited availability of direct measurements. This work presents a combined data-driven and physics-informed approach using Physics-Informed Neural Networks (PINNs) for parameter estimation of vibrating mechanical systems.

A feedforward neural network is first trained using simulated time-domain data of a single degree-of-freedom system. The network learns the relationship between input force and system response, and is able to accurately predict displacement and velocity under different excitation inputs, including sinusoidal, square, and triangular signals. The trained model also demonstrates good generalization when tested on unseen inputs. In addition, the predicted responses are used to construct Frequency Response Functions (FRFs), where the network is able to capture important dynamic features such as resonance frequency and overall system behavior with good agreement to the numerical solution.

However, the above model is not sufficient to enable estimation of physical parameters which govern the motion. The governing equation of motion is incorporated into the training process using a physics-informed loss function. This ensures that the model not only fits the data but also follows the underlying physical laws. Training strategies such as Fourier feature mapping and gradual introduction of physics constraints are used to improve convergence and help the network learn oscillatory dynamics more effectively, especially at higher frequencies. It is observed that when mass and stiffness are estimated simultaneously, the solution becomes non-unique, as different combinations of these parameters can produce similar system responses while maintaining the same natural frequency.

To address this issue, mass is treated as a known parameter, and stiffness and damping are estimated. The proposed approach is validated using experimental data from a rotational SDOF system subjected to forced vibration. The estimated stiffness and damping values show close agreement with experimental results, with errors within 5%. These results demonstrate that the proposed framework provides a simple, reliable, and physically consistent approach for system identification, and is suitable for practical engineering applications involving noisy measurement data.

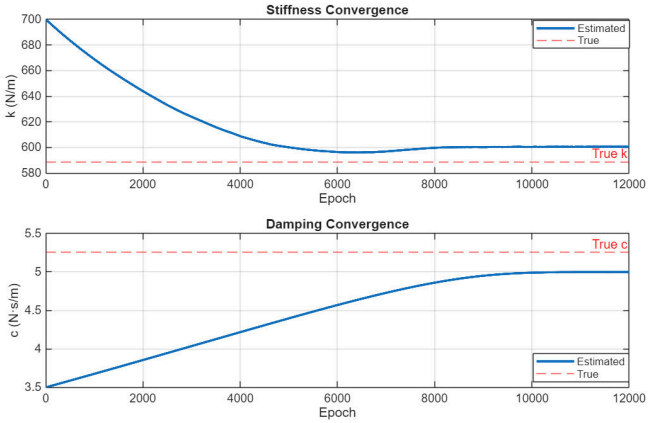

Figure 1: Convergence of mass and stiffness with epochs

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Survival of Mortal Walkers on Landscape of Imperfect Traps

Paramvir Kasana[1], **Poulomi Sadhukhan**[1]

[1]Bennett University, India

We study the survival statistics of random walkers in a heterogeneous landscape with imperfect traps using an agent-based simulation. The environment consists of safe and trapping sites, where each trap encounter reduces a walker's energy without terminating its trajectory — unlike perfect traps, imperfect traps allow the walker to escape and continue exploring, enabling both revisits to previously encountered traps and discovery of new sites. This possibility of repeated exposure is the core of the cumulative damage process, which distinguishes our model from classical first-passage and perfect absorption models [1][2].

Our results show that survival is governed not only by trap density but also crucially by the statistics of revisitation — where skewed revisitation statistics lead to a slower decay of survival probability than predicted by the perfect trap picture. We connect these findings to renewal theory, treating trap encounters as a renewal process, which provides analytical insight into how variability in trap encounter sequences shapes the long-time survival behavior. While approaches based on the number of distinct traps visited offer a complementary perspective [3], the cumulative damage mechanism considered here introduces revisitation as a key factor that goes beyond standard absorption models.

This framework maps naturally onto biological and ecological systems where cumulative exposure determines fate — foraging animals in hostile territories, immune cells navigating heterogeneous tissue, or organisms accumulating toxin exposure in patchy environments [4][5]. Our work bridges agent-based simulation, statistical physics, and biological modeling.

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Robust Quantum Entanglement via Quintic Saturation in Kerr Microresonators

Prashant Singh[1], K. Senthilnathan[1]

[1]Photonics Research Lab, Vellore Institute of Technology, Vellore, Tamil Nadu, India

The birth of dissipative solitons in high-Q microresonators is fundamentally driven by the amplification of zero-point vacuum fluctuations [3]. While classical Lugiato-Lefever dynamics describe temporal stability, the role of higher-order nonlinearities in shaping underlying quantum correlations is vital for high-purity photon-pair generation [1]. We investigate the interplay between competing $\chi^{(3)}$ and $\chi^{(5)}$ nonlinearities, demonstrating that quintic saturation acts as a deterministic stabilizer for quantum correlations near the modulation instability threshold.

The system is modeled using the stochastic quantum Lugiato-Lefever Equation (Q-LLE), where the intracavity operator $\hat{\Psi}$ evolves under dispersion, competing nonlinearities, and Langevin noise $\hat{\xi}$:

$$\frac{\partial\hat{\Psi}}{\partial\tau} = -(1+i\alpha)\hat{\Psi} + i\frac{d_2}{2}\frac{\partial^2\hat{\Psi}}{\partial\theta^2} + i\gamma_1|\hat{\Psi}|^2\hat{\Psi} + i\gamma_2|\hat{\Psi}|^4\hat{\Psi} + F + \sqrt{2}\hat{\xi}$$

The stochastic term $\hat{\xi}(\theta,\tau)$ represents complex Gaussian white noise with zero mean, satisfying the two-time, two-point correlation property:

$$\langle\hat{\xi}(\theta,\tau)\hat{\xi}^{\dagger}(\theta',\tau')\rangle = \delta(\theta-\theta')\delta(\tau-\tau')$$

This noise term models the coupling to the external vacuum reservoir and initiates Spontaneous Four-Wave Mixing (SFWM). Using a stochastic Split-Step Fourier Method (S-SSFM), we track the evolution from this vacuum state, observing sideband growth regulated by nonlinear competition [2].

To validate our simulations, we derive an analytical Joint Spectral Amplitude (JSA) via Bogoliubov-de Gennes analysis. The comprehensive evolution is captured in Fig. 1, which tracks the system from initial vacuum noise to a stabilized comb and highly correlated photon pairs.

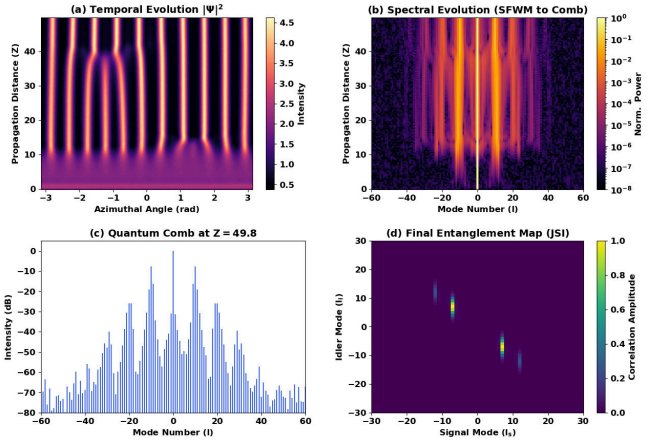

Figure 1: Evolution of the quantum comb. Top panels (a-b) show temporal/spectral waterfall maps. Bottom panels (c-d) display the final stabilized spectrum and the JSI, where $\chi^{(5)}$ saturation maintains localized entanglement hotspots.

As evidenced by the localized hotspots on the energy-conservation diagonal ($l_s = -l_i$), the quintic term effectively filters parametric noise. Unlike purely cubic systems where high pump powers trigger chaotic spectral broadening, quintic saturation constrains energy transfer. This preserves entanglement purity, suggesting that $\chi^{(5)}$ engineering provides a robust pathway for high-dimensional quantum light sources.

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Multiplex Network for El Niño: An Integrative Approach to the dynamics of El Ni~no

Pooja Jain[1], Nivedita Deo[1]

[1]Department of Physics and Astrophysics, University of Delhi, Delhi, India

El Niño is characterized by an irregular increase in sea surface temperatures in the central and eastern tropical Pacific Ocean. Under normal conditions, the easterly wind transports warm surface water westward, supporting rainfall in India and nearby regions. But during El Niño, trade winds weaken, causing warm water to move eastward and disrupting global weather.

Unusual changes in various variables, such as sea surface temperature, sea level pressure, specific humidity, and U-wind, are related to this phenomenon. This phenomenon can significantly impact global weather patterns, leading to various climatic effects across different regions. Understanding this phenomenon is crucial for preparing for potential environmental and economic shifts.

Previously, we studied this phenomenon using a single variable, the temperature. Now, we use a much deeper approach using multiple climatic variables (i.e., sea surface temperature, sea level pressure, specific humidity, and horizontal wind speed) in a multiplex network. By analyzing the data from all four variables, we determine that evaluating the statistics of interaction between two variables yields more insightful results than examining each variable in isolation. Our investigation of multilink and link overlap allows us to identify the most effective combinations for monitoring El Niño. In addition, we assess the multidegree and clustering coefficients across various combinations to pinpoint significant geographical locations. This methodology enables us to identify the most critical variable combinations and key positions relevant to the study of El Niño. This comprehensive analysis allows us to identify patterns and correlations that may have previously gone unnoticed. Ultimately, our findings contribute to a more nuanced understanding of El Niño's impact on climate variability and to facilitate more accurate predictions. We analyze the multiplex network, structure and functions, by taking into account not only sea surface temperature but also surface pressure, specific humidity, and U-wind speed. Using all these variables together helps us to study the dependency of all the variables on each other, which consequently helps us to an integrative understanding of the El Niño phenomena.

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Generation of ultra-short pulses in resonant optical fiber with stimulated Raman Scattering Effect

B. Poojalini[1], B. Kalithasan [2]

[1]PSNA College of Engineering and Technology, Dindigul,India
[2]PSNA College of Engineering and Technology, Dindigul,India

In nonlinear optical fiber communications, soliton propagation occurs. By studying the continuous-wave steady-state solution along the fiber, introducing a tiny perturbation and then analyzed modulational instability (MI) . This is crucial for generating ultrashort pulses and is essential for high-speed optical communication systems. In this work, a steady light beam propagating in an optical fiber doped with a two-level atomic resonant medium is investigated including the effects of stimulated Raman scattering (SRS). The system is modeled using the governed Nonlinear Schrodinger–Maxwell Bloch (NLSE–MB) equations and These equations include Kerr nonlinearity, group-velocity dispersion (GVD), Raman effects, and atomic resonance inside the fiber. These equations describe how modulational instability leads and develops in the system. By applying linear stability analysis (LSA) to the steady-state solutions,the modulational instability properties of the system are examined. The findings show that an imbalance between the Stokes and anti-Stokes components is caused by the SRS effect and the peak MI frequency shifts toward the Raman frequency. Furthermore, non-conventional MI sidebands appear in the normal dispersion regime. Self-induced transparency (SIT) makes the instability more stable and strongly suppresses it. when compared to standard optical fibres. These findings may help in the development of advanced optical fiber communication systems.

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Analysis of Slow-Fast Dynamics in an Electrochemical Reaction

Pratip Dalal[1], Suneet Singh[2]

[1]Indian Institute of Technology Bombay, Mumbai, India

The formic acid electro-oxidation reaction on platinum electrodes exhibits rich nonlinear dynamics driven by the inherent coupling between surface coverage kinetics and electrode overpotential. In this work, a mechanistic triple-pathway reaction model is formulated as a system of nonlinear ordinary differential equations, and its dynamic behavior is systematically characterized through co-dimension one bifurcation analysis, which identifies the CO oxidation potential difference as the critical parameter governing the transition from stable steady-state operation to self-sustained oscillations via a Hopf bifurcation, terminating at a fold bifurcation point. Eigenvalue analysis reveals a pronounced separation between fast and slow timescales inherent to the system, motivating a slow–fast decomposition in which rapid surface adsorption events are distinguished from slow CO accumulation and removal dynamics. Nullcline and phase-space analysis of the fast subsystem expose an S-shaped critical manifold with two stable branches, explaining how the catalyst surface repeatedly switches between a CO-poisoned inactive state and an active state, producing the relaxation and bursting oscillations observed in the full system. Co-dimension two analysis further reveals that the oscillatory behavior arises entirely from the coupling between slow and fast subsystems rather than from the fast chemistry alone, establishing a unified dynamical framework that connects electrochemical kinetics with nonlinear systems theory and provides a foundation for reduced-order modeling and control of formic acid fuel cell systems.

Bi-Directionally Coupled Murali-Lakshmanan-Chua Circuits for Logic Gate Realization

V. H. Preethi[1], M. Sathish Aravindh[2], K. Srinivasan[1], M. Lakshmanan[2]

[1]Department of Physics, Nehru Memorial College, Puthanampatti- 621 007, Tamil Nadu, India (Affiliated to Bharathidasan University, Tiruchirapalli - 620 024, Tamil Nadu, India)

[2]Department of Nonlinear Dynamics, School of Physics, Bharathidasan University, Tiruchirappalli - 620 024, Tamil Nadu, India.

Bidirectional coupled Murali-Lakshmanan-Chua (MLC) circuits represent a nonlinear dynamical system where symmetric coupling induced chaotic interactions and synchronization can be realized. This elegant architecture enhances signal coherence and bifurcation richness, enabling advanced functionalities beyond traditional unidirectional designs. Its robust versatility enables a wide range of transformative applications in nonlinear electronics and unconventional computing. In the present study, our investigation unveils a novel implementation of fundamental and universal logic gates OR/NOR, AND/NAND within the bidirectional coupled MLC circuits by exploiting the attractor in different regions of phase space, and we show that the nonlinear circuit is capable of producing fundamental and universal logic gates. It demonstrates remarkable robustness and tolerance to noise due to its intrinsic nonlinear dynamics and symmetrical coupling. These phenomena can also be experimentally demonstrated. Thus, our work demonstrates that fundamental and universal logic gates can be implemented using a simple nonlinear circuit. This approach could offer a novel way to construct computer architectures.

Acknowledgments

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Second-order Kuramoto model with adaptive simplicial complex

Priyanka Rajwani* and Sarika Jalan

Complex Systems Lab, Department of Physics, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore - 453552, India

priyankarajwani4399@gmail.com

Previous studies on the second-order Kuramoto model have typically considered a constant coupling strength, whereas adaptive coupling schemes, where the interaction strength is modulated by feedback from the collective synchronization measure, remain less explored. In this study, we investigate synchronization in the second-order Kuramoto model with adaptive higher-order (simplicial) interactions on a globally coupled network.

Using a self-consistency approach, we show that in the continuum limit the incoherent state persists with increasing coupling strength, indicating suppression of the forward synchronization transition. However, finite-size systems exhibit a bistable regime, where fluctuations in the order parameter can induce an abrupt transition to synchronization (see Fig. 1). We demonstrate that the adaptation exponent γ regulates both pairwise and higher-order interactions through r_1^γ, thereby controlling the transition points. While inertia and system size affect the forward transition, higher-order coupling governs the backward transition. These results reveal the interplay between adaptive feedback, inertia, finite-size effects, and higher-order interactions in shaping synchronization dynamics.

Model: We consider a second-order Kuramoto model with $2-$simplex interactions and an adaptive coupling framework. The equation of motion of N globally coupled oscillators is given as:

$$m\ddot{\theta}_i = -\dot{\theta}_i + \Omega_i + \frac{K_1 r_1^\gamma}{N}\sum_{k=1}^{N}\sin(\theta_k - \theta_i) + \frac{K_2 r_1^\gamma}{N^2}\sum_{k=1}^{N}\sum_{l=1}^{N}\sin(2\theta_k - \theta_l - \theta_i),$$

where the generalized complex order parameter is defined as: $z_p = r_p e^{\iota\psi_p} = \frac{1}{N}\sum_{k=1}^{N} e^{\iota p\theta_k}$.

Results:

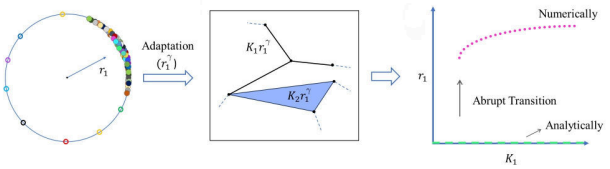

Figure 1: Schematic diagram illustrating a dynamical snapshot of the second-order Kuramoto model with higher-order interactions and adaptive coupling.

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Frustration-Induced Collective Dynamical States in Pulse-Coupled Adaptive Winfree Networks

R. Anand[1], V K Chandrasekar[1], R. Suresh[1]

[1]Centre for Nonlinear Science and Engineering, Department of Physics, School of EEE, SASTRA Deemed to be University, Thanjavur, 613 401.

We investigate collective dynamics in a pulse-coupled adaptive Winfree network under the influence of a frustration (phase-lag) parameter. The coupling strengths coevolve according to a Hebbian adaptation rule and self-organize to support a wide variety of collective states. We observe frequency-clustered states, entrainment, bump states, bump–frequency cluster states, antipodal and multi-antipodal cluster states, chimera states, and incoherent dynamics. Notably, we report for the first time the spontaneous emergence of entrainment, bump, and bump–frequency cluster states in an adaptive network *without* any external forcing. To systematically characterize these regimes, we introduce three complementary measures of incoherence based on (i) time-averaged frequencies, (ii) instantaneous phases, and (iii) mean frequencies per bin. These measures enable the construction of one- and two-parameter phase diagrams that clearly delineate transitions between distinct dynamical states. Furthermore, we analytically derive the stability condition for the frequency-entrained state, which shows excellent agreement with numerical simulations. Our results highlight the crucial role of frustration-mediated plasticity in shaping rich self-organized dynamics in pulse-coupled adaptive networks.

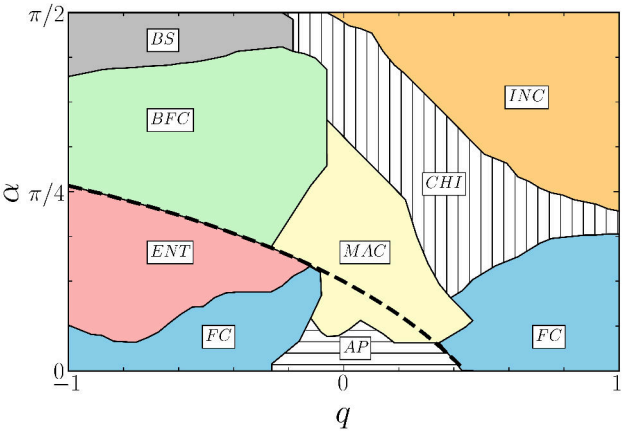

Figure 1: Two-parameter phase diagram of dynamical states in the (q, α) space. The initial conditions for θ_i, and k_{ij} are uniformly distributed over the intervals $[0, 2\pi)$, and $(-1, 1)$, respectively. The black dashed lines indicate analytical curve for frequency entrained state.

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Stationary $1/f^{\alpha}$ noise in discrete models of the Kardar-Parisi-Zhang class

Rahul Chhimpa and Avinash Chand Yadav

Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221 005, India

In discrete models describing growing rough interfaces of the Kardar-Parisi-Zhang universality class, we examine height fluctuations at a fixed site as a function of time in the monolayer unit. For small systems, we show that it is possible to reach the stationary state. We compute the two-time autocorrelation and power spectra independently. The correlation function remains non-exponential and vanishes after a correlation time that diverges with system size. As a result, the power spectra display a lower cutoff that maintains constant power. In the nontrivial frequency regime, we observe $1/f^{\alpha}$-type scaling with the spectral exponent 5/3. Finite-size scaling reveals that the temporal correlation function follows a dynamic scaling. Our findings, supported by scaling-theoretical arguments, establish that the fluctuations are wide-sense stationary, implying applicability of the Wiener-Khinchin theorem.

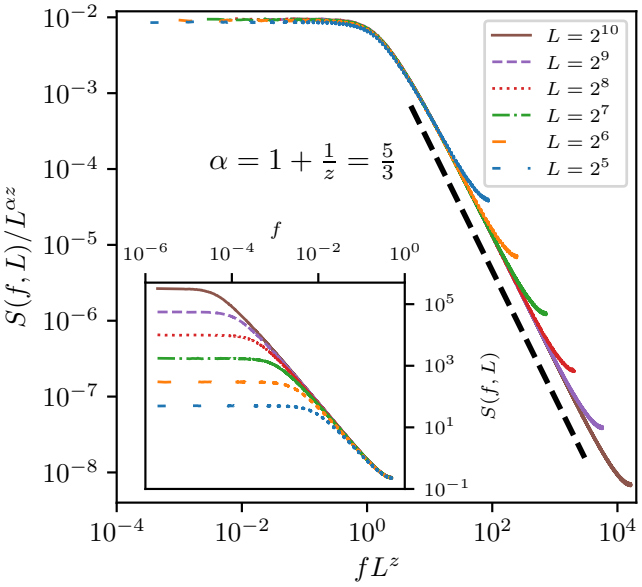

Figure 1: Inset: The power spectrum $S(f, L)$ of the height noise $\delta h_L(t)$ in the Kim-Kosterlitz model. The system size varies from 2^5 to 2^{10}. The initial 10^3 measurements are discarded as transient, and the signal length is $T = 2^{20}$. To reduce noise in the PSD for each curve, we perform an ensemble average over 10^4 independent realizations. Main panel: The data collapse of the power spectra as shown in the inset. The dashed (black) line guides the slope of 5/3.

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Engineering Solitons in Spin–Orbit and Rabi-Coupled Bose–Einstein Condensates

K. Rajaswathi and P. Muruganandam

Department of Physics, Bharathidasan University, Tiruchirappalli 620 024, Tamil Nadu, India

Solitons are self-reinforcing wave packets that maintain their shape through a balance between nonlinearity and dispersion. We investigate the stability and dynamics of dark and bright solitons in a quasi-one-dimensional binary Bose-Einstein condensate with spin-orbit and Rabi couplings, confined in a box potential. By numerically solving the coupled Gross-Pitaevskii equations, we analyze the ground states and dynamical evolution as functions of intra- and interspecies interaction strengths and coupling parameters. Our results reveal a rich phase diagram exhibiting stable single-soliton states, oscillatory modes, and multi-soliton complexes. For moving solitons, we observe pronounced asymmetry in their dynamics: dark solitons propagate forward while emitting backward-traveling sound waves, indicative of energy dissipation, whereas bright solitons display markedly reduced dissipation. The Bogoliubov-de Gennes excitation spectrum corroborates these results, confirming the stability of the observed stationary and dynamical states. Furthermore, we explore nonequilibrium behavior by simulating quenches in the Rabi coupling, demonstrating that it serves as an effective control parameter for soliton manipulation. Our findings highlight that the interplay of spin–orbit and Rabi couplings provides a powerful means to engineer and control solitonic excitations in multicomponent quantum gases.

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A Nonlinear Observable-Space Extension of S-Map for Chaotic Time Series Forecasting

Raktim Ray[1], Bhavya Bansal[1], Partha Sharathi Dutta[1]

[1]Department of Mathematics, Indian Institute of Technology Ropar, India

Forecasting non-linear and chaotic dynamical systems remains a major challenge due to the complex geometry of their underlying attractors [2, 5]. The Sequential Locally Weighted Global Linear Map (S-Map) is a popular method in empirical dynamic modelling that approximates local dynamics through weighted linear regression in reconstructed state space [4, 1]. However, the standard S-Map framework assumes locality and linearity in the original embedding coordinates.

In this work, we propose a feature-lifted extension of S-Map in which delay-coordinate vectors are transformed through non-linear observable functions before forecasting. Polynomial, Chebyshev, Legendre, Hermite, Fourier, and Gaussian radial basis functions (RBFs) are investigated as observables. Unlike conventional S-Map, neighbourhood weights are computed in the transformed observable space. This creates a new geometry on the reconstructed attractor and redefines dynamical similarity through observable-space distances.

The proposed framework is evaluated on the Lorenz and Rössler systems, as well as the BATS empirical data [3]. Results demonstrate substantial improvements in forecasting accuracy over standard S-Map, with orthogonal polynomial and Gaussian RBF observables providing the most consistent gains. We show that the improvement arises from a combination of enhanced nonlinear approximation capability, improved numerical conditioning, and a modified distance metric that better captures local dynamical structure.

These results indicate that nonlinear observable transformations provide a promising direction for extending empirical dynamic modelling beyond conventional linear local approximations.

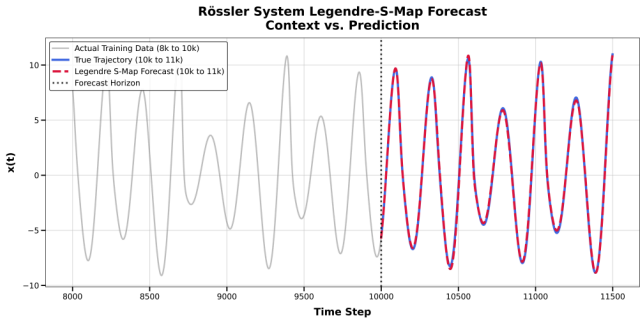

Figure 1: Multi-step forecasting of the Rössler system using the Legendre observable-space S-Map. The blue curve represents the true trajectory, while the red dashed curve denotes the forecast obtained after transforming the reconstructed states through Legendre polynomial observables.

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Network Structure Shapes Pollinator Collapse under Rapid Shifts in Demographic Rates with Random Fluctuations

Ravi Kumar K[1], **Partha Sharathi Dutta**[2]

[1,2]Indian Institute of Technology Ropar, Rupnagar, Punjab, India

Fast and fluctuating environmental change threatens the persistence of species in ecological communities. Plant-pollinator mutualistic networks, which support biodiversity and ecosystem functioning, are particularly vulnerable to such disturbances. Although environmental variation is known to modify demographic rates and weaken mutualistic interactions, how its pace and stochasticity jointly affect the stability of mutualistic networks remains largely unknown. Here, we analyze a high-dimensional mutualistic network model [1] in which environmental change is characterized by time-varying mortality and competition rates that exhibit noisy fluctuations. A reduced two-dimensional model reveals that sufficiently fast parameter change can trigger rate-driven pollinator collapse [2], which is further expedited by noise. These dynamics persist in the high-dimensional mutualistic network. Using 30 empirical plant-pollinator communities, we show that network structure strongly modulates vulnerability to environmental change (Figure 1): higher connectance and nestedness increase tolerance to rapid environmental change across noise intensities, whereas higher modularity reduces stability, leading to collapse at lower rates of change. Overall, our results highlight that the pace and variability of environmental change interact with network structure to shape the stability and persistence of mutualistic communities.

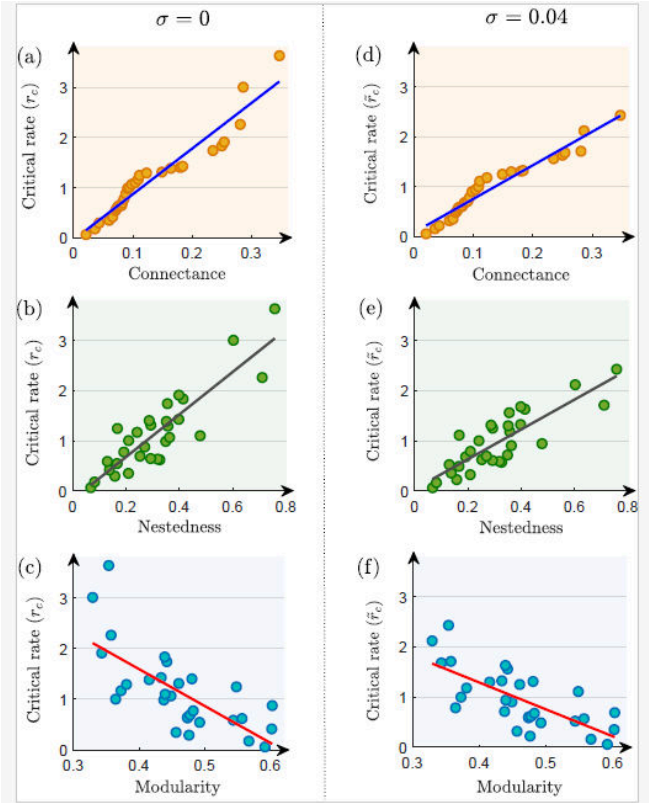

Figure 1: Network structures: connectance, nestedness, modularity vs critical rates of the external input.

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A coupled Nonlinear Oscillator Model to explore Emergent Dynamics in Plant Hydraulics

Riddhika Mahalanabis[1], **Balakrishnan Ashok**[1]

[1]Complex Systems & Soft Matter Physics Lab, Centre for Applied Sciences, International Institute of Information Technology Bangalore (IIIT-B), 26/C, Electronics City Phase-1, Hosur Road, Bangalore 560100, India.

Water transport in plants is a dynamically regulated and spatially distributed process, integrating root uptake, xylem conduction, and stomatal transpiration. Traditional models of plant hydaulics usually take a microscale approach or rely on static or lumped-parameter electrical analogs for a whole-plant level [1, 2], and thus fail to capture experimentally observed behaviours, such as phase lags, flow hysteresis, and self-sustained oscillations.

In this work, we introduce a novel holistic modeling framework that treats the plant as a system of three coupled nonlinear oscillators, representing the root, stem, and leaf, respectively [3]. Each segment of the plant is modeled using a distinct nonlinear oscillator tailored to its physiological role. Coupling between these compartments is informed by plant anatomy: unidirectional from root to stem, and bidirectional between stem and leaf (as illutrated in fig.1).

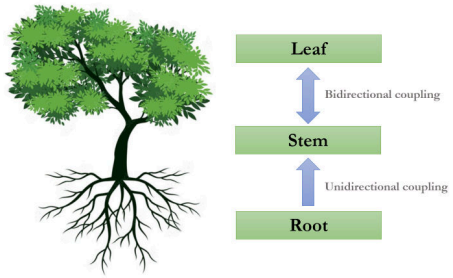

Figure 1: Proposed coupled oscillator model for root-stem-leaf system. Root is unidirectionally coupled to stem, whereas stem and leaf are bidirectionally coupled.

Through numerical simulations, we uncover rich dynamics including multistability, bifurcation, and transition to chaos. Our model reproduces key experimental signatures such as period doubling and amplitude jumps, and demonstrates how nonlinearity and intercompartmental coupling shape global flow dynamics. It also successfully captures feedback and synchronization phenomena observed in real plants.

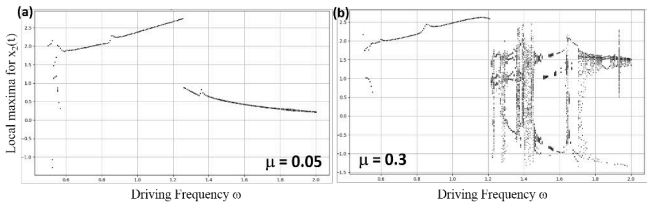

Figure 2: Bifurcation diagram showing chaotic regime appearing in the stem when leaf is highly nonlinear.

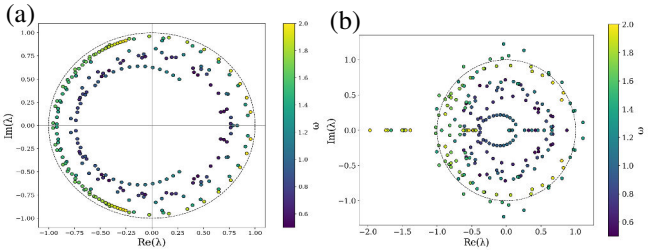

Figure 3: Position of the floquet multipliers indicating (a) stable system behaviour for a less nonlinear leaf & (b) unstable system behaviour for a highly nonlinear leaf.

This model, while simplifying a highly complex biological system, offers a tractable starting point to advance our theoretical understanding of plant hydraulics. It provides a baseline for exploring environmental responses, resilience, and control strategies of plant water transport and can be extended to understand engineered or artificial systems that emulate plant-like water regulation, with potential applications in biomimetic microfluidics, soft robotics, or agricultural system modeling.

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Experimental three-state Chimera in active rotors

Ratan sarkar[1], SapnaYadav[1],Charo I. del Genio[2],Stefano Boccaletti[3],P. Parmananda[1]

[1]Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
[2]Institute of Smart Agriculture for Safe and Functional Foods and Supplements, Trakia University, Stara Zagora 6000, Bulgaria
[3]Institute of Complex Systems, National Research Council, Sesto Fiorentino 50019, Italy

Chimera states are a remarkable manifestation of symmetry breaking, wherein identical units spontaneously split into coherent and incoherent groups. The term "chimera" itself is inspired by the mythological creature having parts of different animals, reflecting the coexistence of distinct dynamical behaviors within a single system. Here, we experimentally demonstrate the existence of a three-state chimera in a system of four identical camphor-infused elliptical rotors, each pivoted at a corner of a square base. When placed on a water surface, the rotors self-propel and rotate due to Marangoni-driven flows. Chemical coupling mediated through the shared water interface gives rise to three distinct collective dynamical states, namely a synchronized one, an antisynchronized one and an incoherent one. Our results validate recent theoretical work about three-domain chimeras in reaction-diffusion models, providing new insights into nonlinear dynamics and suggesting that this new type of chimera may be observed in a broad class of physical systems.

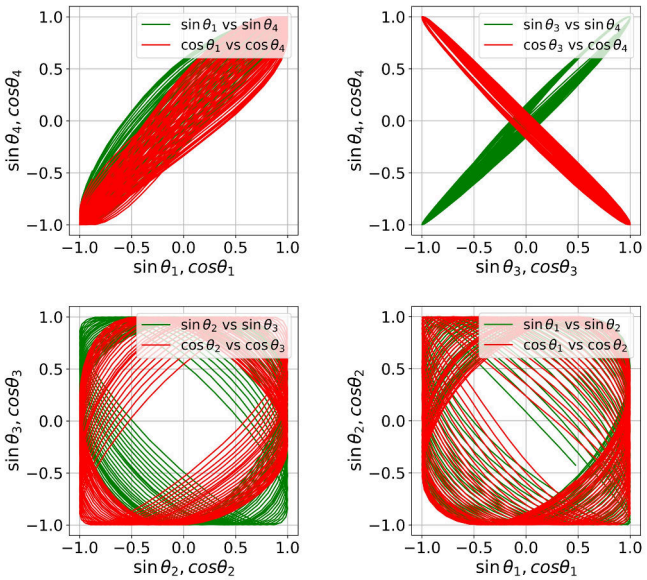

Figure 1: Emergence of a three-state chimera. The Lissajous plots of $\sin\theta_i$ and $\cos\theta_i$ for the four camphor rotors confirm the exitence of a three-state chimera in our system. Rotor (1,4) synchronized pair, Rotor (3,4) anti-synchronized pair, Rotor (2,3) and (1,2) pairs are de-synchronized pair.

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Bipartite Network-Based Assessment of Rainfall-Streamflow-Sediment Connectivity in the Ganga River Basin

Ripunjay Pandey[1], Apoorva Sharad[1], Sanjeev Kumar Jha[1], Kundan Kandhway[1]

[1]Indian Institute of Science Education and Research, Bhopal, Madhya Pradesh, India, 462066

Rainfall, streamflow, and sediment transport are strongly interconnected components of river-basin dynamics, yet their relationships are commonly examined separately using conventional pairwise approaches. Such approaches often fail to capture the spatially distributed and temporally lagged propagation of rainfall signals through hydrological and sediment systems. This study develops a bipartite complex network framework to investigate rainfall-streamflow-sediment connectivity across the Ganga River Basin. Daily rainfall data from 692 rainfall stations and streamflow and sediment records from 207 hydrometric gauges were analysed for 1991-2020. Rainfall stations were represented as driver nodes, whereas streamflow and sediment gauges were represented as response nodes. Hydrologically meaningful rainfall-gauge candidate pairs were identified using the same sub-basin membership and DEM-derived upstream catchment constraints. Lagged rainfall-response links were evaluated over a 0 to 7-day window using two approaches: a positive lagged-correlation network for whole-year and JJAS conditions, and a JJAS extreme-event network based on station-wise 90th percentile thresholds. Separate rainfall-streamflow (RQ) and rainfall-sediment (RS) bipartite networks were constructed.

The results reveal distinct rainfall-response structures in the RQ and RS networks. DEM-upstream filtering produced 2,707 hydrologically valid rainfall-gauge candidate pairs for the JJAS extreme-event analysis, from which 271 RQ and 271 RS links were retained using the top 10 event-support criterion. The retained links showed strong physical consistency, as mean rainfall-gauge distance increased systematically with increasing lag.

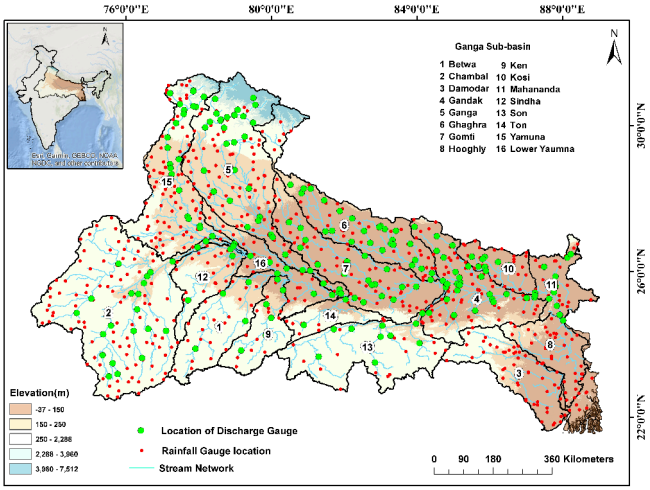

Figure 1: Study area shows the spatial distribution of rainfall stations, hydrometric gauges, stream network, elevation zones, and sub-basins within the Ganga River Basin.

The results demonstrate that streamflow connectivity is more spatially integrated, whereas sediment connectivity is more heterogeneous and influenced by geomorphic and sediment-availability controls. The proposed bipartite framework provides a transferable approach to identifying rainfall-influence pathways, hydrological-response hubs, extreme-event propagation pathways, and priority zones for basin-scale monitoring and management. The study is ongoing, and the results will be presented at the conference.

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The evolution of chaotic hysteresis in a quasiperiodically forced Murali–Lakshmanan–Chua circuit

S. Chinnamuthammal[1,2], G. Sivaganesh[3], K. Srinivasan[1]

[1]Department of Physics, Nehru Memorial College, Puthanampatti - 621 007, Tamilnadu, India (Affiliated to Bharathidasan University, Tiruchirapalli - 620 024, Tamilnadu, India)
[2]Department of Physics, Sri Sarada Niketan College of Science for Women, Kodangipatti, Karur - 639 005, Tamilnadu, India
[3]Department of Physics, Alagappa Chettiar Government College of Engineering and Technology, Karaikudi - 630 003, Tamilnadu, India

The present work reports the evolution of chaotic hysteresis in a second-order non-autonomous chaotic circuit[cite: 177]. A quasiperiodically forced Murali–Lakshmanan–Chua (MLC) circuit is investigated to analyze the emergence of hysteresis behavior under varying system parameters[cite: 178]. It is observed that the variation of the DC offset factor within a specific range leads to the onset of chaotic hysteresis, accompanied by the formation of a strange non-chaotic attractor (SNA) in the system dynamics[cite: 179]. To the best of our knowledge, this work presents the first report on the evolution of hysteresis in a quasiperiodically forced system exhibiting SNA dynamics[cite: 180].

The presence of SNA is confirmed through singular spectral analysis, validating the non-chaotic yet fractal nature of the attractor[cite: 184]. Furthermore, the experimental realization of chaotic hysteresis is supported by numerical simulations, showing strong agreement between theoretical and experimental results[cite: 185]. The system exhibits hopping dynamics between two distinct phase planes, indicating multistability in the circuit behavior[cite: 186].

Acknowledgments

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A Data-Driven Hybrid Model Framework for Epidemiological and Economic Assessment of Foot and Mouth Disease in Kerala's Livestock Sector

Saby C. Sebastian[1]*, Justin Davis Kollannur[1], Karun Kaniyamattam[2]

[1] Department of Veterinary Epidemiology and Preventive Medicine, College of Veterinary and Animal Sciences, Mannuthy, Thrissur, Kerala, India.
[2]Department of Animal Science and AgriLife Research, Texas A&M University, College Station, USA.
sabysebastian234@gmail.com

Foot and mouth disease (FMD) continues to pose a substantial threat to livestock productivity and economic stability in endemic regions. This study develops a data driven hybrid modeling framework integrating Agent Based Modeling (ABM) and System Dynamics (SD) to quantify both epidemiological dynamics and economic impacts of FMD at the farm level in Kerala, India. The model is parameterized using Kerala specific livestock demographic data, incorporating realistic herd structures comprising calves, heifers, pregnant cows, and milking animals. Within each herd agent, disease progression follows a compartmental SEIRC structure (susceptible–exposed–infectious subclinical–infectious clinical–carrier–recovered), capturing heterogeneous transmission dynamics and carrier persistence. The ABM layer enables representation of herd level autonomy and intervention targeting, while the SD framework ensures computational efficiency in simulating within-herd processes. A comprehensive economic module is integrated into the model, quantifying milk production losses, treatment expenditures, mortality losses, and control costs. Simulation experiments were conducted under multiple vaccination scenarios to evaluate the role of herd immunity in outbreak mitigation. Results indicate that in the absence of vaccination, FMD outbreaks can result in economic losses of approximately Rs. 185 crore. Implementation of vaccination without achieving herd immunity reduces losses to Rs. 37.56 crore, whereas achieving effective herd immunity further reduces total losses to approximately Rs. 171702.00 even after accounting for vaccination costs. The findings underscore that herd immunity thresholds critically determine both epidemiological outcomes and economic resilience, particularly under varying transmission intensities. The hybrid framework advances contemporary data driven epidemiological modeling by coupling disease dynamics with economic intelligence, providing a robust decision-support tool for optimizing vaccination strategies and resource allocation.

Correlated Environmental Responses and Tipping in Multispecies Ecological Systems

Sagar Karmakar, Amit Samadder, Joydev Chattopadhyay

Agricultural and Ecological Research Unit, Indian Statistical Institute, 203, B.T Road, Kolkata- 700108, India.

Regime shifts can drastically alter species abundances, destabilize ecological interactions, and generate serious consequences for ecosystem services and human livelihoods. While deterministic tipping points have been widely studied, real ecosystems are continuously exposed to stochastic environmental forcing, which may induce transitions before deterministic thresholds are crossed, a phenomenon known as noise-induced critical transition.

In multispecies communities, environmental variability influences system dynamics not only through temporal autocorrelation (the "color" of noise), but also through the correlation in species responses to shared environmental fluctuations. This latter mechanism, referred to as species response correlation, remains largely unexplored in the context of ecological tipping. We did a systematic investigation of some two-species ecological models representing competitive and mutualistic interactions under stochastic forcing. The environmental response structure is incorporated through correlated noise processes (ξ_i)

$\xi_i = k\xi_{i-1} + \sqrt{1-k^2}$ (term determining similarity in responses)

Our results reaffirm that stronger positive temporal autocorrelation in environmental fluctuations increases the likelihood of tipping, regardless of interaction type. In contrast, stronger positive species response correlation has contrasting effects depending on the nature of species interactions. In competitive systems, it tends to delay the onset of tipping by enhancing system resilience. However, in mutualistic systems, the effect is reversed: correlated responses can facilitate earlier transitions by amplifying positive feedbacks. These findings reveal that the similarity in how species perceive and respond to environmental variability is a crucial, yet often overlooked, determinant of ecological resilience and the probability of sudden regime shifts.

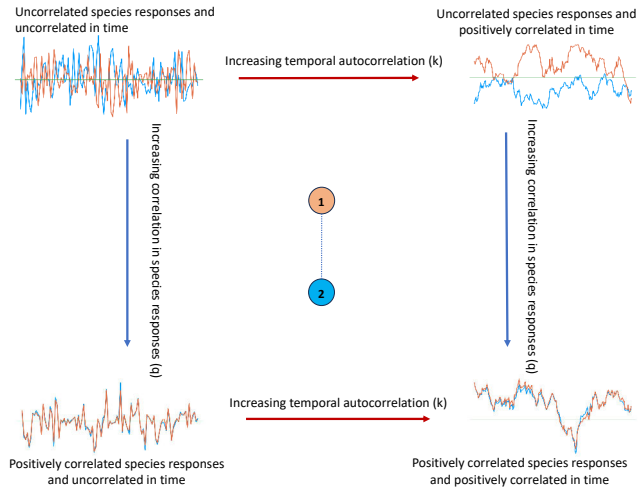

Figure 1: Example of an arbitrary pair of noise generated for interacting species 1 and 2. The lower row represents the species response correlation coefficient at high values, indicating more synchronized responses. Conversely, the right column depicts the higher temporal correlation coefficient.

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Evolution of synchronization during transitions to self-sustained periodic oscillations

Sagar Sedani[1,2], Beeraiah Thonti[1,2], R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600 036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600 036, India

Complex dynamical systems often exhibit transitions from chaos to order as system parameters are varied. Turbulent reactive flows provide a prominent example in which thermoacoustic instability manifests as self-sustained periodic oscillations induced by variation in a system parameter (fuel–air ratio). Thermoacoustic instability arises from nonlinear coupling between acoustic pressure fluctuations (p') and unsteady heat release rate ($\dot{q}'$), forming a feedback loop. Transition from chaotic fluctuations to periodic oscillations can be studied as mutual synchronization between p' and $\dot{q}'$ [1]. In a complex dynamical system, variation of a secondary parameter (flame holder position) can intricately change the nature of the transition from continuous to explosive, giving rise to five distinct transition types—a phenomenon we call the metamorphosis of the transition to periodic oscillations [2]. Despite experimental evidence of this metamorphosis, the underlying dynamical mechanism remains unexplored.

We use the probability of recurrence from reconstructed phase spaces to track how the nature of synchronization between p' and $\dot{q}'$ evolves across the metamorphosis. Our results demonstrate that coupling between these two nonidentical oscillators strengthens as the system parameter is varied toward the onset of self-sustained periodic oscillations, leading to gradual synchronization despite abrupt amplitude jumps in acoustic pressure fluctuations between dynamical states. Overall, six distinct synchronization states are identified across the metamorphosis (Fig. 1).

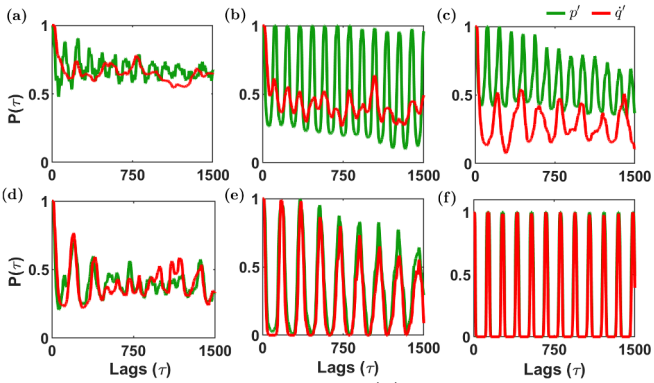

Figure 1: Probability of recurrence ($P(\tau)$) as a function of time lag (τ) (in samples) for the phase space trajectories of acoustic pressure fluctuations (p', green) and unsteady heat release rate fluctuations ($\dot{q}'$, red), shown for different synchronization states across the metamorphosis of transition to self-sustained oscillations. (a) desynchronized state; (b) phase synchronization between periodic p' and aperiodic $\dot{q}'$; (c) imperfect phase synchronization; (d) phase synchronization between two aperiodic oscillators; (e) phase synchronization between two periodic oscillators; (f) generalized synchronization between two periodic oscillators. For all the $P(\tau)$ plots in this study, the parameters used are embedding dimension = 6, time delay = 1.75 ms, and recurrence threshold = 30% of the maximum size of the attractor in reconstructed phase space.

Acknowledgement

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Novel Nondegenerate Soliton Structures in the Coupled Nonlinear Schrödinger Equation: A Gram Determinant Darboux Approach

K. N. Santhiya[1], P. S. Vinayagam[1,*]

[1]Department of Physics, PSG College of Arts and Science, Coimbatore
*Corresponding author email: psvinayagam11@gmail.com

Nondegenerate vector solitons exhibit the rich internal structures due to the presence of distinct spectral parameters associated with each component of the system [1]. We employ the Darboux transformation (DT) method together with the Gram determinant formulation to construct higher-order solutions of the coupled nonlinear Schrödinger (Manakov) system. Unlike the conventional DT representation, the compact Gram determinant form enables the systematic generation of higher-order analytical solutions efficiently [2]. Using this framework, we construct nondegenerate soliton solutions up to the Nth order, while here illustrating the interaction dynamics of the fifth- and sixth-order solutions.

Analysis of these higher-order solutions reveals several novel nonlinear wave structures. In particular, we observe four distinct types of interaction dynamics: (i) collisions between two soliton molecule and an individual soliton, (ii) collisions between three soliton molecules, (iii) localized Rogon-like centred spikes emerging at the interaction region, and (iv) collision patterns associated with beating solitons. These phenomena produce rich spatiotemporal dynamics characterized by multi-peak bound structures and intricate interaction patterns.

Our results demonstrate that the Gram determinant Darboux framework provides a powerful analytical tool for exploring complex higher-order nonlinear structures and offers new insights into the dynamics of nondegenerate solitons in integrable vector nonlinear Schrödinger systems. These results reveal rich interaction dynamics in the Manakov system, including soliton molecules, Rogon-like spikes, and beating interactions. Such higher-order structures are relevant in nonlinear optics and Bose–Einstein condensates, where multicomponent interactions influence energy localization.

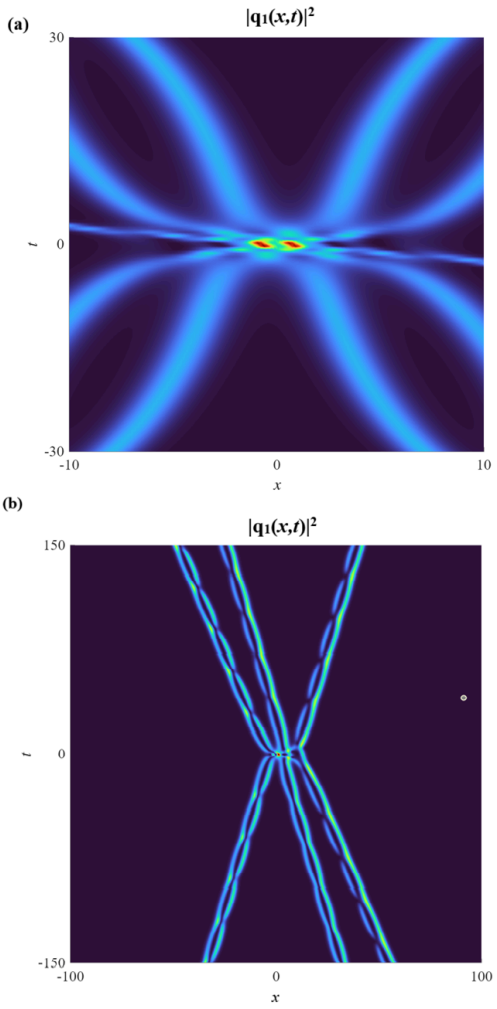

Figure 1: Interaction dynamics of higher–order nondegenerate solitons in the q_1 mode: (a) localized Rogon-like centred spikes emerging at the interaction region (fifth-order) and (b) collision between three soliton molecules (sixth-order).

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Experimental evidence of community switching en route to global synchronization

Sapna Yadav[1], Taniya Khatun, Heirtami Paswet, and P. Parmananda[1]

[1] IIT Bombay

Complex networks are made up of communities wherein dynamics occur. Here, a community is defined as an ensemble of identical Wien-bridge oscillators that are nearly synchronized. We explore experimental evidence of community switching, i.e., a subset of oscillators in a community synchronizing their frequencies to those of the other community.

We demonstrate this phenomenon by varying the network connectivity and interaction strength. Employing Wien-bridge oscillators, we study experimentally, as well as in LTspice simulations the phenomenon where an oscillator synchronizes its frequency to that of its neighboring community en route to global synchronization (Figs. 2 and 3).

Our results are in agreement with numerical simulations of the Kuramoto model reported by Kato and Kori in their novel work involving community switching [1]. Due to the presence of noise, hysteresis is also observed in our experiment but not in LTspice simulations.

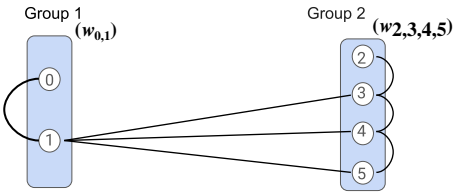

Figure 1: Schematic diagram of the two-community network with 7 edges. Oscillators in the two communities have frequencies $\omega_{0,1}$ and $\omega_{2,3,4,5}$ respectively. However, due to noise, oscillators in a community have slightly different frequencies for the experiments.

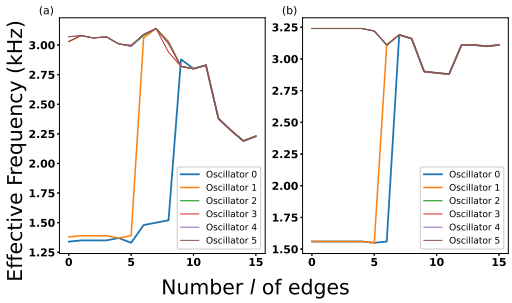

Figure 2: Community switching en route to global synchronization demonstrated in a network of six Wien-bridge oscillators by varying the network topology for a fixed coupling strength (K). (a) Here: $\omega_0 = 1.48$ kHz, $\omega_1 = 1.53$ kHz, $\omega_2 = 3.38$ kHz, $\omega_3 = 3.42$ kHz $\omega_4 = 3.20$ kHz and $\omega_5 = 3.20$ kHz. Experimentally, community switching occurs in the domain between $l = 5$ and $l = 6$ (b) Here: $\omega_{0,1} = 1.56$ kHz and $\omega_{2,3,4,5} = 3.24$ kHz. In LTspice simulation, we observe community switching occurring again in the domain between $l = 5$ and $l = 6$.

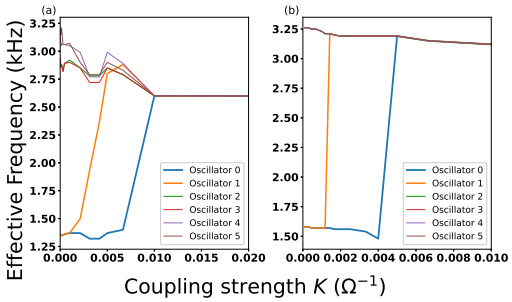

Figure 3: Community switching en route to global synchronization demonstrated in a network of six Wien-bridge oscillators on varying the coupling strength for a fixed topology. To enhance the visibility of the domain in which switching occurs, the x-axis has been limited to $0.02\Omega^{-1}$ and $0.01\Omega^{-1}$ for (a) and (b) respectively. (a) Here: $\omega_0 = 1.43$ kHz, $\omega_1 = 1.53$ kHz, $\omega_2 = 3.38$ kHz, $\omega_3 = 3.42$ kHz $\omega_4 = 3.20$ kHz and $\omega_5 = 3.20$ kHz. Oscillator 1 undergoes community switching between K = 0.002 and $0.005\Omega^{-1}$ (b) Here: $\omega_{0,1} = 1.56$ kHz and $\omega_{2,3,4,5} = 3.24$ kHz. In this LTspice simulation, oscillator 1 undergoes community switching between K = 0.0012 and 0.0014 Ω^{-1}.

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Synchronisation of Nanomechanical Oscillators

Satya Vemuri[1], Soumya Kanti Das[1], Jinsha P[1], Chandan Samanta[1]

[1]Department of Physics, Indian Institute of Science Education and Research, Bhopal, India

In this work we explore synchronisation in two-dimensional graphene nanomechanical oscillators. Synchronisation is a ubiquitous phenomenon observed in many natural as well as engineered systems. These graphene based devices are inherently nonlinear and offer wide range of parameter tunability. We design and model comprehensive experimental studies that probe the phenomenon exploiting the unique properties of these devices.

We first study a single self-sustained oscillator, analyse and compare two methods for implementing feedback-induced self-oscillations, and examine the role of thermomechanical noise on the oscillator's phase. The same framework developed for the oscillator, which employs scaling using the actual device parameters, is then used to study injection locking and obtain the Adler equation of the form

$$\psi' = \nu + \beta - p\sqrt{1+\beta^2}\cos(\psi)$$

where p is the strength of the synchronising force,ν is the difference in their frequencies, β is the tunable nonlinearity parameter of the oscillator, and ψ is the phase difference.

We then focus on mutual synchronisation in two coupled oscillators, where we systematically study all combinations of diffusive and direct coupling, both positional and velocitive, deriving generalised Adler equations for each case and characterising the locking behaviour and nonlinear frequency pulling. The two coupling schemes accessible through our device designs allow a controlled exploration of the full coupling parameter space: the electrically coupled device offers independent tunability of coupling strength and nature, while the mechanically coupled device, where the coupling is intrinsic and potentially mixed, serves as a verification of the theoretical framework under less controlled conditions.

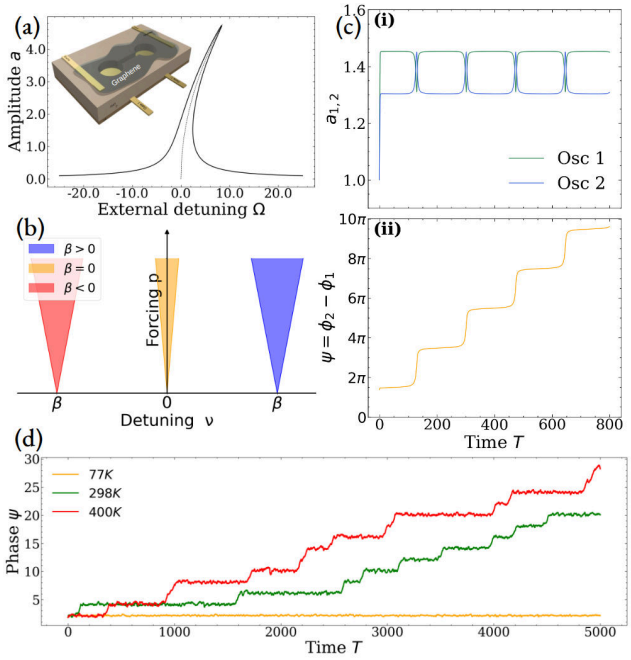

Figure 1: (a) Frequency response of the nanomechanical resonator. *Inset:* Illustration of the device layout. (b) Synchronisation region given by the Adler equation for three different β values depicting the variation of both position of the center and with of synchronisation as a function of β. (c) Numerical simulation of thermomechanical noise induced phase slipping within the synchronisation regime at three different temperatures. (d) Mutual Synchronisation: Phase slipping and resulting amplitude modulation in reactively coupled oscillators.

The systematic setup of this work, from the implementation of self-oscillation in nanomechanical systems to the comprehensive characterisation of the effects of coupling on synchronisation, enables us to explore more complex coupling schemes, such as those found in the real world, where coupling cannot always be neatly categorised.

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Interacting subsystems, emerging thermoacoustic instabilities: A complex systems view of turbulent thermoacoustic system

Sreelakshmi Pallayil[1,2], Manikandan Raghunathan[1, 2], Beeraiah Thonti[1, 2], and R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai, Tamil Nadu 600036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai, Tamil Nadu 600036, India

Complex systems with many interacting components undergo critical transitions, where a change in a control parameter leads to an abrupt qualitative shift in the state of the system. A turbulent thermoacoustic system, comprising interacting subsystems of acoustics, hydrodynamics, and unsteady heat release rate [1], exhibits such behavior. As the control parameter varies, the system transitions to thermoacoustic instability (TAI), a catastrophic phenomenon characterized by self-sustaining, large-amplitude periodic oscillations in acoustic pressure, arising from nonlinear interactions among the three subsystems.

Previous studies have proposed various mechanisms for the occurrence of different TAI regimes based on frequency matching between the subsystems [2, 3]; however, the spatiotemporal evolution of local interactions as they transition from one TAI regime to another remains unclear.

To investigate these nonlinear interactions experimentally, we employ tools from synchronization theory, particularly the Phase-Locking Value (PLV) on the experimental measurements (acoustic pressure fluctuations $p'(t)$, global heat release rate $\dot{Q}(t)$, local heat release rate $\dot{q}(x,y,t)$, and velocity field $V(x,y,t)$). The vorticity field $\omega_z(x,y,t)$ is obtained from $V(x,y,t)$ using the finite difference method, and circulation $\Gamma(t)$ is subsequently computed. PLV quantifies phase synchronization between two oscillators, a' and b', as

$$PLV_{a'b'} = \frac{1}{N}\left|\sum_{t=1}^{N} e^{i\Delta\phi_{a'(t)b'(t)}}\right| \qquad (1)$$

In this study, we identify three distinct states of TAI: S_{TAI}-1, S_{TAI}-2, and S_{TAI}-3, as the system transitions from the state of stable operation to full-blown TAI, each characterized by varying dominance of subsystem interactions. Temporal dynamics of normalized p', $\dot{Q}'$, and Γ' (refer to Fig.1 (a-c)), along with PLV distributions between p' - $\dot{q}'$ (see Fig.1 (d-f)) and p' - ω_z', (refer to Fig.1 (g-i)) reveal that changes in the global coupling behavior are attributed to local interactions among p', $\dot{q}'$, and ω_z'. In S_{TAI}-1, p' is strongly coupled with Γ', while its coupling with $\dot{Q}'$ remains weak. In S_{TAI}-2, coupling shifts to p' - $\dot{Q}'$. In S_{TAI}-3, all three subsystems are coupled with slight phase differences, signifying strong subsystem interaction leading to high-amplitude TAI. These findings provide experimental evidence of how local interactions among subsystems influence the overall dynamics of the system and the occurrence of distinct TAI regimes.

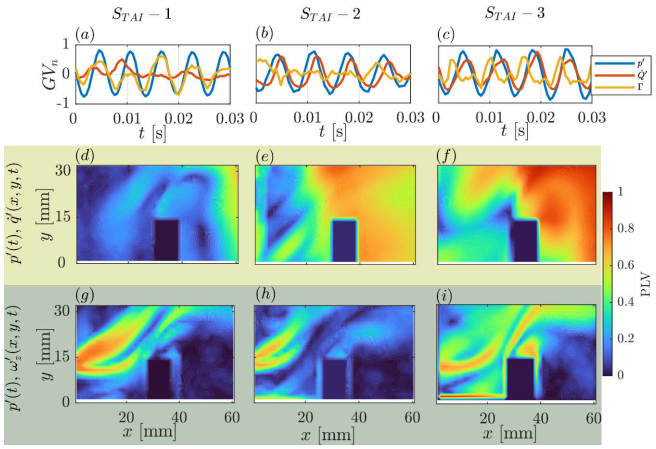

Figure 1: Time series of the normalized forms of p', $\dot{Q}'$, and Γ' during three different regimes of thermoacoustic instability (TAI) are given (a-c). Figure legend represents the color code for each global variable GV_N. Symbol '′' followed by any quantity represents the fluctuations, calculated by subtracting the time-averaged quantity from the instantaneous value. The spatial distributions of PLV between p' & $\dot{q}'$ (d-f), as well as p' & ω_z' (g-i), are shown for each of the three TAI regimes.

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Inevitability of degenerate Hopf bifurcation en route change of criticality of Hopf bifurcation in a prototypical thermoacoustic system

Sandra James Thomas[1,2], Rohit Radhakrishnan [1,2], Sivakumar Sudarsanan [1,2], R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[2]Centre of Excellence for studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600036, India

A wide variety of systems in nature are susceptible to oscillations due to the interplay between energy and stability. Such oscillations become self-sustained when a positive feedback mechanism counteracts the natural damping of the system. Self-sustained oscillations emerge from a quiescent operation state through a supercritical or subcritical Hopf bifurcation upon variation of a control parameter [1]. In the present work, we study the criticality of the Hopf bifurcation in a prototypical thermoacoustic system, a horizontal Rijke tube.

The experimental results of Matveev [2] suggest that the system, a horizontal Rijke tube, undergoes bifurcation when the control parameter, the heater power, crosses a critical value. Etikyala and Sujith [1] showed that a prototypical thermoacoustic system, the Rijke tube, exhibits a change of criticality of Hopf bifurcation upon the variation of a secondary control parameter - the mass flow rate of air.

Kuehn and Bick [3] gave a mathematical argument that a generic two-parameter family must lead to a change of criticality, where the emergence of these first-order (subcritical) transitions occurs from second-order (supercritical) transitions upon the continuous sweep of the first Lyapunov coefficient from a negative to a positive value. Kuznetsov [4] provides a rigorous explanation of the presence of a generalized Hopf (Bautin) bifurcation, which occurs when the first Lyapunov coefficient vanishes, causing a degenerate Hopf bifurcation.

Although the degenerate Hopf bifurcation has been primarily a theoretical concept, the present study provides its first experimental evidence. We perform experiments in a prototypical thermoacoustic system - the Rijke tube, to observe how the change of criticality of bifurcations occurs. We observe that the change of criticality of Hopf bifurcation occurs from a regime of supercritical Hopf to a regime of subcritical Hopf bifurcation, which takes place through a transition regime as observed in Fig. 1. The transition regime encompasses the degenerate Hopf bifurcation, and the bifurcations in the transition regime exhibit characteristics of both supercritical and subcritical Hopf bifurcations.

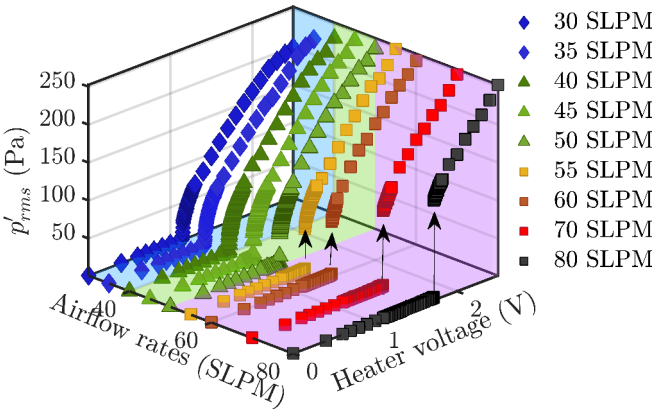

Figure 1: The change of criticality of bifurcations occurs from supercritical Hopf to subcritical Hopf bifurcation via a transition regime of bifurcations upon the systematic variation of the secondary control parameter. Here, the primary control parameter is the heater voltage (ordinate), and the secondary control parameter is the airflow rate (abscissa).

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Vorticity-Induced Multipole States in a Dipolar Bose-Einstein Condensate under Two-Dimensional Confinement

S. Sanjay[1], S. Saravana Veni[2], Boris A. Malomed[3]

[1,2]Department of Physics, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham, Coimbatore, 641112, India.
[3]Department of Physical Electronics, School of Electrical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel, and Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica, Chile.

We study the stability, and dynamics of three-dimensional elongated multipole quantum droplets in a dipolar Bose-Einstein condensate (BEC) confined by a two-dimensional trap combining harmonic and Gaussian potentials. The system is described by an extended Gross–Pitaevskii equation including dipole–dipole interactions and Lee–Huang–Yang corrections, which enable the stabilization of self-bound states.

Multipole solutions are analyzed under both weak and strong confinement. Stable states with vorticity $S \leq 2$ follow the relation $n = 2S$, while higher-order structures emerge only in the strong confinement regime for sufficiently large particle number, supporting configurations up to $S = 6$. We examine how chemical potential, energy, and peak density vary with system parameters. Notably, below a critical particle number, the ground state shifts from $S = 0$ to $S = 1$.

Dynamical simulations indicate that energetic stability does not always guarantee robustness, as higher-vorticity states tend to become unstable or evolve into lower-S configurations. These findings underline the interplay of confinement, dipolar effects, and quantum fluctuations in determining the stability of multipole quantum droplets.

The objective of this work is to investigate the formation, stability, and dynamics of multipole states in a dipolar Bose-Einstein condensate of strongly dipolar NaCs molecules. Recent advances using microwave shielding techniques [1] have enabled the creation of NaCs condensates with dipolar interaction strengths ranging from $1000a_0$ to $25000a_0$ (a_0 is the Bohr radius), significantly exceeding that of ^{164}Dy atoms ($a_{\mathrm{DDI}} = 130.8a_0$). Such strong dipolar interactions make NaCs a promising platform for exploring self-bound quantum states.

Previous studies [2] examined three-dimensional multipole structures in ^{164}Dy under toroidal confinement, where the zero-vorticity state remains stable, while configurations with $1 \leq S \leq 6$ exhibit only transient stability. However, stable self-bound states carrying vorticity in strongly dipolar molecular systems remain largely unexplored.

In vortex-carrying quantum droplets with vorticity S, the centrifugal kinetic energy associated with phase winding, scaling as S^2, drives the density outward and competes with both external confinement and Lee–Huang–Yang (LHY) repulsion. This competition gives rise to the spontaneous formation of multipole droplet structures, which is a key focus of the present work.

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Generation of Ultra-Short Pulses in a doped fibre Bragg grating with Nonlinear Management effects

R.Santhiya[1], B.Kalithasan[2]

[1]PSNA College of Engineering and Technology, Dindigul, India.
[2]PSNA College of Engineering and Technology, Dindigul, India.

The propagation of continuous waves (CW) in a uniformly doped fibre Bragg grating (FBG) is an important topic in nonlinear dynamics.Previous studies have majorly focussed on passive (undoped) gratings modelled by nonlinear coupled mode equation (NLCM) without including the effects of resonant atomic interaction and nonlinear management. Moreover, Modulational Instability (MI) in normal dispersion regime either occurs with a threshold input power or it does not occur in conventional FBG and its effective control near the photonic bandgap (PBG) has not been investigated thoroughly.

In this work, we investigate the propagation of CW in a doped FBG system using a set of nonlinear coupled – mode Maxwell – Bloch (NLCM-MB) equations, which includes the effects of both periodic structure and resonant atomic effects. Linear Stability Analysis (LSA) is performed to examine the onset of MI in both normal and anomalous dispersion regimes. The results show that in contrast to conventional FBG systems, the addition of nonlinear management enables the generation of MI in normal dispersion regime without any threshold condition. It also shows that the resonant atomic detuning plays an important role in the formation of non-conventional MI sidebands near the PBG edges which influences the instability growth rate. This system provides potential applications in high speed optical communication systems and ultrafast optical signal processing.

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Swarmalators with Frequency-Weighted Interactions

R. Senthamizhan, R. Gopal*, and V. K. Chandrasekar†

Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613 401, India
*gopalphysics@gmail.com, †chandru25nld@gmail.com

Swarmalators are oscillators that simultaneously synchronize their internal phases and coordinate their spatial positions, coupling the dynamics of phase oscillators with self-propelled particle motion [1]. While much of the analytical progress has been made in one-dimensional (1D) solvable models where agents are confined to a ring [2], the role of heterogeneous interaction rules remains largely unexplored in this framework. In the Kuramoto literature, frequency-weighted coupling—where the coupling strength is scaled by the agents' natural frequencies—has been shown to produce explosive synchronization and a variety of complex dynamical states [3]. We extend this idea to swarmalators and investigate its consequences on the coupled position-phase dynamics [4].

We consider N swarmalators on a ring, each described by its spatial position $x_i \in [-\pi, \pi]$ and internal phase $\theta_i \in [-\pi, \pi]$, governed by

$$\dot{x}_i = v_i + \frac{J}{N}\sum_{j=1}^{N} \sin(x_j - x_i)\,|\omega_i|\cos(\theta_j - \theta_i), \quad (1)$$

$$\dot{\theta}_i = \omega_i + \frac{K}{N}\sum_{j=1}^{N} \cos(x_j - x_i)\,|\omega_i|\sin(\theta_j - \theta_i), \quad (2)$$

where v_i and ω_i are drawn from a Cauchy distribution with zero mean and unit half-width. The parameters J and K control the spatial and phase coupling strengths, respectively. The factor $|\omega_i|$ in both couplings ensures that agents with larger intrinsic frequencies exert a proportionally stronger influence on the collective, introducing a nontrivial form of quenched heterogeneity.

Through numerical simulations and self-consistency analysis, we identify three collective states: (i) the *asynchronous state* (AS), with no position-phase correlation; (ii) the *phase-wave state* (PW), exhibiting a diagonal correlation $x \approx \pm\theta$; and (iii) the *bistrip mixed state* (BM), characterized by two antipodal clusters each internally split into frequency-sign-dependent substrips.

By introducing sum-difference coordinates $\epsilon_i = x_i + \theta_i$ and $\eta_i = x_i - \theta_i$ and the complex order parameters $W_\pm = S_\pm e^{i\psi_\pm} = N^{-1}\sum_j e^{i(x_j \pm \theta_j)}$, we derive the critical thresholds analytically. The AS state loses stability when $J_{+,c} = (J+K)/2 = 2\pi$, obtained from a linearized self-consistency integral over the locked population. The PW–BM boundary is determined by the criterion

$$\frac{JK}{|K|\,\pi(J^2 - K^2)} \ln\left(\frac{|J|}{|K|}\right) = 1, \quad (3)$$

while the hysteretic onsets of the PW and BM branches are located via saddle-node bifurcations through numerical continuation of the self-consistency fixed-point equations. The BM substrip separation is predicted as $\Delta[\sin\phi^*] = 2/(KS_+)$, which agrees quantitatively with simulations. These results provide a comprehensive analytical framework for the frequency-weighted 1D swarmalator model.

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Dynamics of Coupled Hindmarsh-Rose Neuronal Networks

Shamal Lad[1], Chandrakala Meena[2], D. V. Senthilkumar[1]

[1]Indian Institute of Science Education and Research Thiruvananthapuram, India
[2]Indian Institute of Science Education and Research Pune, India

The human brain is one of the most complex and challenging systems. It contains about 86 billion neurons and many more synapses. Neuronal networks self-organise in intricate patterns that are essential for brain function. These spatiotemporal patterns play a key role in neuronal communication, plasticity, and cognitive processes. Rhythmicity and synchrony among large ensembles of neurons are essential for numerous neurobiological processes, primarily resulting from inter-neuronal synaptic interactions. In this study, we explore the emergence of diverse spatiotemporal patterns in a ring network of neurons, modelled using the Hindmarsh-Rose (HR) square wave bursting model, with local inhibitory chemical synaptic coupling and global electrical gap junctions. The dynamics of each node in a network of coupled neurons are modelled as,

$$\dot{x}_i = ax_i^2 - x_i^3 - y_i - z_i + \lambda_{\text{el}} \sum_{j=i-p}^{i+p} (x_j - x_i) - \frac{}{2p}(V_s - x_i) \sum_{j=i-1}^{i+1} c_{ij}\Gamma(x_j) \quad (1)$$

$$\dot{y}_i = (a+\alpha)x_i^2 - y_i \quad (2)$$

$$\dot{z}_i = c(bx_i - z_i + e) \quad (3)$$

Where x is the membrane potential, y is the fast current due to ion transport, and z is the slow current. λ_{syn} and λ_{el} are the synaptic chemical coupling strength and the electrical coupling strength, respectively. The functionality of the electric coupling term is governed by a linear function, and that of the chemical coupling is governed by a sigmoidal function. Other parameters are chosen so that we obtain square-wave bursting [1].

Our research demonstrates that at a high λ_{syn}, low λ_{el} leads to a mixed oscillatory state (MOS), where desynchronized neurons are interspersed among those that are oscillating in synchrony [2]. As λ_{el} increases, the system transitions into amplitude death(AD), and at low λ_{syn} values, the transition to synchronisation (SYN) occurs. The threshold for these transitions is sensitive to the λ_{syn} (at lower λ_{syn}, for transition, lower λ_{el} is required compared to that required for the higher λ_{syn}). Furthermore, at high λ_{el} and low λ_{syn}, we observe synchronisation (SYN), which shifts to amplitude death(AD) as the λ_{syn} increases. To distinguish the states, we used the global order parameter and snapshots of the phases and time series of oscillators. Finally, depending on these two coupling parameters, the system shows three distinct states: the mixed oscillatory state(MOS), amplitude death (AD), and synchronisation (SYN) (Fig.1).

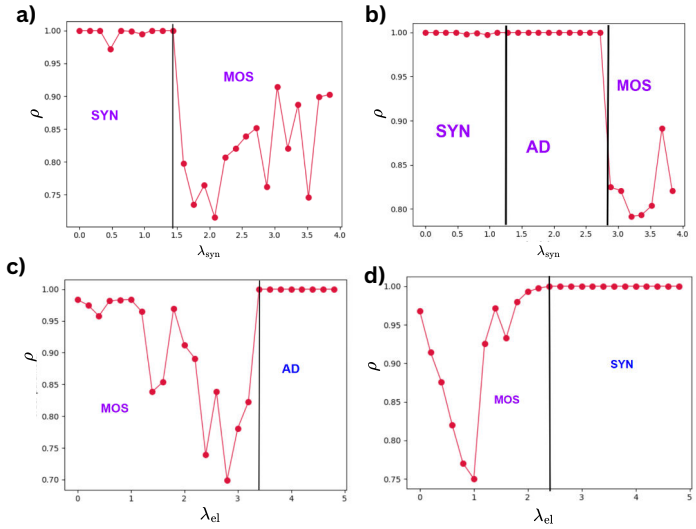

Figure 1: Global order parameter plots:For (a) and (b) λ_{el} is constant [a]λ_{syn}=2.29,(b)λ_{syn}= 3.33. For (c) and (d) λ_{syn} is constant (c) λ_{el}= 2.5 , (d) λ_{syn}=0.33

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Untangling the mechanism of the brain at work

Sheksha Dudekula[1], **Aradhana Singh**[1]

[1]Department of Physics, IISER Tirupati, Andhra Pradesh, India

Our brain is a complex machine responsible for all we can feel, understand, and act on. We are still in the process of understanding how it works. More or less, what we know about the brain comes from analysing data generated by different imaging techniques, with Electroencephalography (EEG) being one such technique. To add to the existing understanding of the brain, we analysed EEG data across various states: three task states of binary decision-making and the resting state. All these datasets correspond to the eye-opening state. We investigated in detail the topology of positive and negative correlations between various brain regions. Since each time series corresponding to a task reflects a brain state, this analysis allows us to unveil the topology the brain adopts for processing and acting on information in these particular task states. Considering the EEG-specific topographical modules, we find that the significant positive and negative correlations exhibit different topologies, modular and anti-modular, respectively. Moreover, the strength of these properties depends on the frequency band and state, with the resting state deviating markedly from the task states in the high-frequency gamma bands.

Our work is under review, and details of it can be found in [1].

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

Shivam Kumar, Sudeshna Sinha and Rajeev Kapri

Department of Physical Sciences
Indian Institute of Science Education and Research Mohali
Sector 81, SAS Nagar, Punjab 140306, India

Classical models, such as SIR (Susceptible-Infected-Recovered) and SIRS (Susceptible-Infected-Recovered-Susceptible), are widely used for disease modeling. While the SIR model assumes that individuals acquire lifelong immunity after recovery, the SIRS model accounts for waning immunity over time. Standard models based on deterministic ODEs include constant rates of infection (β) and recovery (γ) [1]. We propose a modified cellular-automata based SIRS model [2], to understand the dynamics of an infectious disease with temporary immunity, in a fixed population. The modifications introduce stage-dependent dynamic infection rates, and direct and indirect transmission modes, with distinct zones of influence across Moore (8 neighbours) and von Neumann (4 neighbours) neighborhoods. The direct transmission is strong and short-ranged, limited to nearest-neighbour zones, whereas indirect transmission is weak and long-ranged influencing up to fourth-nearest-neighbours, with the influence decaying with distance. We implement the model on a lattice of linear dimension L, with $N = L^2$ sites, where each site represents an individual. For stage-dependent infection rates, we first consider uniform stage-independent infectivity f_k, and then go on to consider three sets of stage-dependent infectivities, analogous to the primary waves of COVID-19. We find that high direct-transmission infectivity leads to a peak in infections followed by an absorbing state with no infecteds in the population. In contrast weak infectivity yields infection persistence. We quantify this trend by evaluating a persistence Order Parameter given by the time and ensemble-averaged fraction of infecteds, evaluated after transience. Examining the dependence of the persistence order parameter on infectivity f_k, reveals an optimal window of infection persistence. For infectivities lower or higher than this range we obtain an absorbing state with no remaining infecteds. Upon adding an independent indirect transmission mode, we have find that infection can persist even for infectivity values where direct transmission alone leads to an absorbing state. The simulations across Moore and von Neumann neighborhoods suggests that the neighbourhood with fewer neighbors supports infection persistence. We have also introduced a reinfection probability and find that the critical reinfection probability leading to persistent infection tends to zero in the thermodynamic limit.

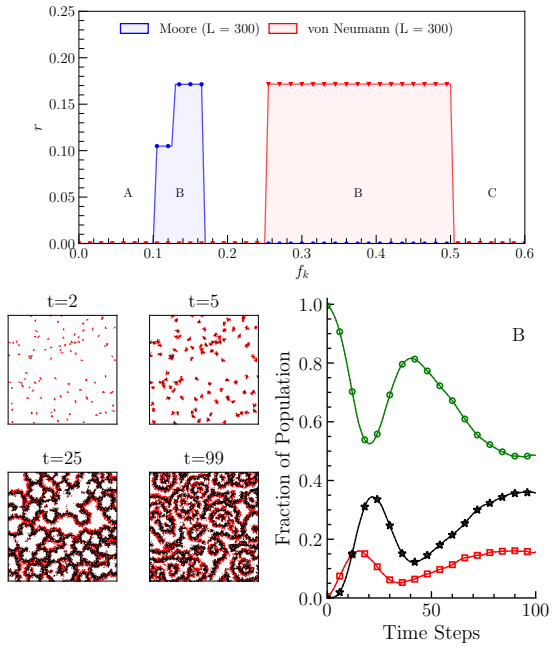

Figure 1: The top panel shows the persistence Order Parameter r versus direct-transmission infectivity f_k, exhibiting 3 regimes: (A) Absorbing, (B) Persistent, and (C) Absorbing. The lower panel shows representative snapshots of the evolving population, alongside the corresponding time series of the fraction $S/N, I/N, R/N$, for the Moore neighbourhood, at infectivity $f_k = 0.14$ which falls in regime (B).

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Enhanced sensing of Blood Plasma using SPR based D-shaped PCF with Silver-coated layer

Shobika M.M[1], V. Devika[2], M.S. Mani Rajan[1]

[1]University College of Engineering Ramanathapuram (Anna University), Tamil Nadu, India
[2]Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, India

shobikamuthiah@gmail.com

A Photonic crystal fiber (PCF) based optical sensors have gained significant attention for biomedical sensing applications due to their high sensitivity and compact structure [1,2]. In this work, a D-shaped PCF based surface plasmon resonance (SPR) sensor is numerically analyzed using COMSOL Multiphysics (version 5.4). The proposed structure consists of a silica background with periodic air holes, where the air hole radius is fixed at 2.2 μm and the pitch is maintained at 2.8 μm. A silver layer with a thickness of 47.2 nm is employed as the plasmonic material to enable SPR-based sensing [1]. The analyte (blood plasma) is placed over the Silver-coated D-shaped surface, and its Refractive index is varied from 1.2714 to 1.3309 to represent different biological conditions. The optical response of the structure is studied over a wavelength range of 0.5 μm to 2.2 μm.

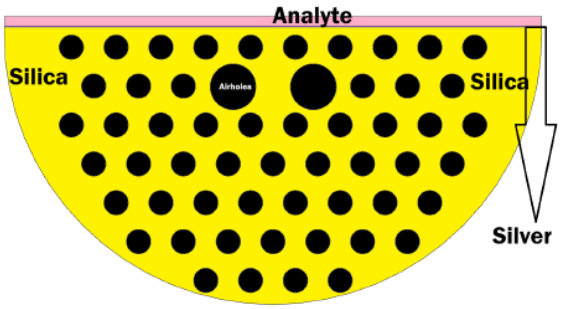

Figure 1: Schematic diagram of the proposed D-shaped PCF-SPR sensor, where the Silver layer is shown at the flat boundary surface.

The simulation data is extracted and processed to obtain the real and imaginary parts of the effective refractive index, where the imaginary part indicates confinement loss and exhibits a resonance peak corresponding to SPR [1]. The resonance characteristics are analyzed for selected refractive index values. It is observed that the resonance wavelength shift is more significant for larger variations in refractive index, while smaller changes result in minimal shift. Hence, distinct refractive index points are considered to evaluate the sensing performance effectively [2].

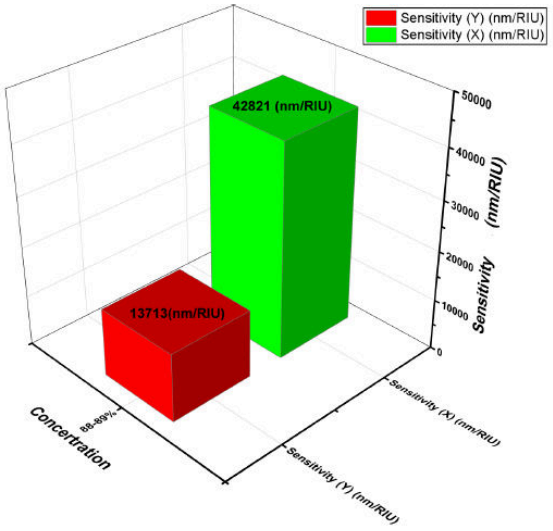

Figure 2: Sensitivity analysis of D-shaped PCF based SPR sensor showing orthogonal mode configurations.

The sensitivity of the proposed sensor is calculated based on the wavelength shift, and a maximum sensitivity of 42821 nm/RIU is obtained for the selected range. The results demonstrate that the proposed D-shaped PCF-SPR sensor can effectively detect variations in blood plasma properties and can be utilized as a compact and label-free platform for biomedical sensing applications [2].

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Detecting and distinguishing tipping points via a data-driven approach

Shubam Kandyal, and Partha Sharathi Dutta

Department of Mathematics
Indian Institute of Technology Ropar, Rupnagar, Punjab, India

A lot of attention has been paid in predicting and classifying bifurcation-induced tipping or critical transitions in low-dimensional dynamical systems. However, most existing methods are developed for specific systems or particular bifurcation scenarios, and therefore do not provide a unified framework capable of accurately forecasting and distinguishing tipping associated with diverse bifurcations. This limitation becomes more pronounced in real-world systems, where the governing equations are often unknown and only observational spatial or temporal data are available.

Recent advances in data-driven modeling have enabled the reconstruction of dynamical systems from observational data, offering a promising alternative to traditional model-based approaches. Over the years, progress has been made in deriving governing equations from data, thereby enabling a strong foundation for data-driven system identification [1, 2]. Despite this progress, accurately predicting tipping remains a challenging problem. Motivated by this gap, we develop a data-driven framework to infer the underlying governing equations from pre-transition data.

The inferred model is then analyzed within a bifurcation-theoretic framework to detect the onset of tipping. This allows us to estimate the tipping (bifurcation) point, determine the type of bifurcation, and investigate the qualitative behavior of the system in the post-transition regime. By leveraging the reconstructed model, we can extend predictions beyond the observed data and gain insight into the system's future evolution. In addition, the model allows systematic exploration of the parameter space, enabling tracking of changes in stability and hence identifying early signatures of an impending transition. The framework is robust to limited and noisy data, which makes it suitable for practical applications where measurements are often imperfect.

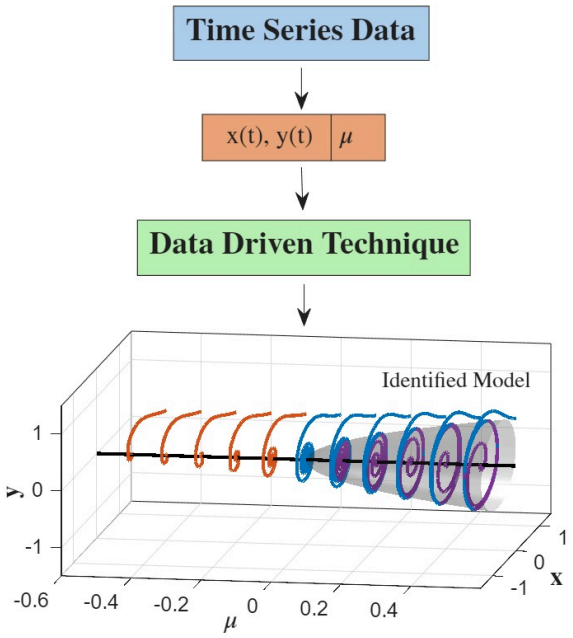

Figure 1: A system that exhibits Hopf bifurcation has been discovered from time series data.

Our approach provides a systematic and interpretable framework for forecasting and distinguishing critical transitions from temporal data. It effectively bridges the gap between data-driven system identification and classical bifurcation analysis and offers improved generality across diverse classes of dynamical systems. This work underscores the potential of combining sparse identification techniques with dynamical systems theory for robust and scalable prediction of tipping phenomena.

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Diffraction-induced Spectral anomaly in non linear media

Shubham Bhardwaj, Soumendu Jana

Department of Physics and Material Science, Thapar Institute of Engineering and Technology, Patiala, Punjab, India, PIN-147004.

This work presents diffraction-induced spectral switching (SS) and highlights the role of nonlinearity. SS is the anomalous spectral behavior near phase singularities—points of zero intensity where the optical phase is undefined. Around these points, the diffracted spectrum changes sharply, and at a specific observation (critical) angle, it splits symmetrically into two equal parts. A slight deviation above or below this angle causes the spectrum to shift toward either the red or blue side, enabling switching between spectral regions simply by adjusting the observation angle or detector position. This effect has strong potential for applications in all-optical logic, computation, data processing, and sensing [1].

SS in nonlinear media remains unexplored, even though nonlinear interactions could enrich and enhance the performance of SS-based devices, especially for optical data processing and computing. In this work, we present a theoretical framework for diffraction-induced SS in nonlinear media. We consider light diffracted through a rectangular aperture.

The initial electric field $E(x, y, 0, t)$ at the aperture plane is given by: $E(x, y, 0, t) = \exp\left(-\frac{x_0^2+y_0^2}{w_0^2}\right) U(t)$, where w_0 is the beam waist, $U(t)$ is the temporal profile of the pulse, $U(t) = \exp\left(-\frac{(1+\iota C)t^2}{2T^2}\right) \exp(-\iota\omega_0 t)$, where T is the pulse duration, C is the chirp parameter and ω_0 is the central frequency of the pulse. The initial electric field in the frequency domain can be obtained by the Fourier transform of the above field.

Now, the Fresnel-Kirchhoff integration gives rise to the electric field after diffraction and propagating distance through a linear medium as:

$$E(x, y, z, \omega) = \frac{1}{i\lambda z} \exp(ikz) \iint E(x_0, y_0, 0, \omega) \times \exp\left[\frac{ik}{2z}\left((x - x_0)^2 + (y - y_0)^2\right)\right] dx_0 dy_0$$

The diffraction-induced power spectrum is thus given by $I(x, y, z, \omega) = |E(x, y, z, \omega)|^2 = I_0(\omega)M$. Here, M is the modifier (i.e., effect of the aperture) given by:

$$M(\alpha_x, \alpha_y, z, \omega) = \frac{\left[\frac{2z_0}{c}\omega\right]^2}{16\left[1 + \left(\frac{2\omega z}{c}\right)^2 \frac{1}{z_0^2}\right]} \times \exp\left[-\frac{2(\alpha_x^2 + \alpha_y^2)\frac{\omega}{c}}{\left[1 + \left(\frac{2\omega z}{c}\right)^2 \frac{1}{z_0^2}\right]}\right] \times \{\text{erf}(C_1^*) - \text{erf}(C_2^*)\} \times \{\text{erf}(C_3^*) - \text{erf}(C_4^*)\}.$$

Now, if the diffracted light passes through a nonlinear (say, Kerr nonlinear) medium, the above integral will be modified as:

$$E(x, y, z, \omega) = \frac{1}{i\lambda z} \exp(ikz) \iint \exp(i\Phi_{NL}) E(x_0, y_0, 0, \omega) \times \exp\left[\frac{ik}{2z}\left((x - x_0)^2 + (y - y_0)^2\right)\right] dx_0 dy_0,$$

where Φ_{NL} is the nonlinear phase modulation introduced by the nonlinear media: $\Phi_{NL} = k_0 n_2 L I = k_0 n_2 L |U|^2$, where n_2 is the Kerr nonlinear coefficient and L is the length of the Kerr medium (here we consider a thin slab). Following those steps for a linear medium, one can obtain the power spectrum of the diffracted light for a nonlinear medium too.

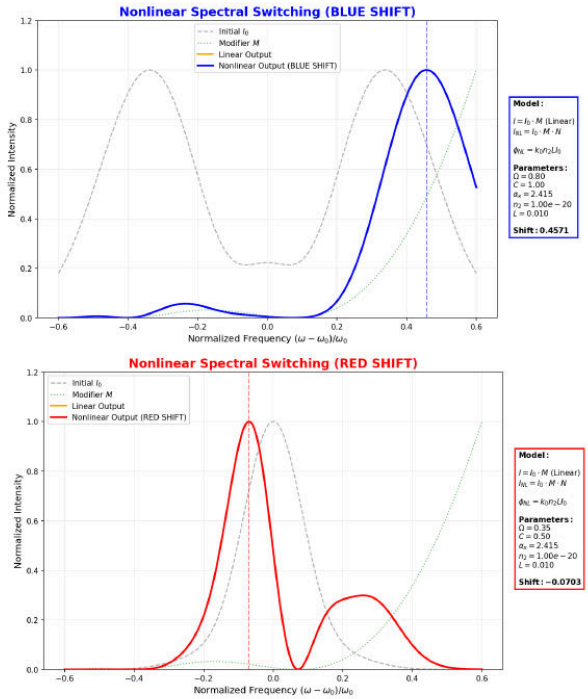

Figure 1: Demonstration of a typical switching phenomenon (red shift and blue shift) with initial intensity. Normalized on-axis power spectrum for different parameters are shown above.

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Neurochaos Learning from The Double Pendulum

Sri Uma Maheshwari V[1], Jyoti Prakash Nayak[1], Nithin Nagaraj [2]

[1]National Institute of Science Education and Research (NISER), Bhubaneswar
[2]Complex Systems Programme, National Institute of Advanced Studies (NIAS), IISc. Campus, Bengaluru

Neurochaos Learning (NL) is a brain inspired learning algorithm that uses chaotic neurons in a single layer [1] and yields state-of-the-art classification performance. Drawing inspiration from biological neurons which are known to exhibit chaos, neurochaos learning implements its architecture by performing nonlinear feature transformation. Until now, NL architectures used various mathematically simulated chaos from 1D maps such as the Generalized Lüroth Series (GLS) as neurons. In this study, instead of GLS neurons, we employ real physical data from a double pendulum, a well known chaotic system to perform the feature transformation in Neurochaos Learning for classification on 8 publicly available datasets.

The Double Pendulum set-up consists of two rigid rods, connected between them and pivoted to a fixed support set up on an optical bread board, using well greased hinges. To facilitate visual tracking, the rod ends were marked with distinct colors, red and blue. Using a phone mounted on a tripod stand, multiple 30 to 45 second videos were captured by releasing the rods from different initial angles. The trajectory data was extracted using a custom OpenCV-based color detection algorithm (see Fig. 1).

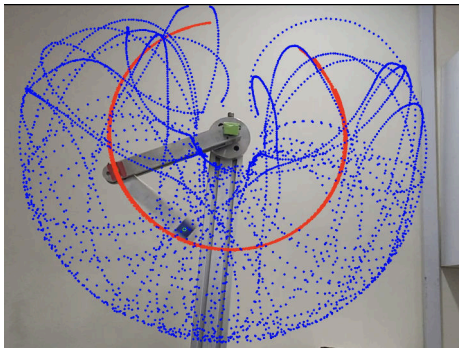

Figure 1: The Double Pendulum. The movement of the two rigid rods are depicted in *red* and *blue*. The chaotic blue trajectory is used in Neurochaos Learning in this study.

The Tracking Algorithm used predefined HSV (Hue-Saturation-Value) ranges to generate masks that isolated the red and blue markers, which were refined using erosion and dilation processes to remove noise, after which the contours were selected. The centroid of the largest contour was computed to obtain the exact (x, y) coordinates.

To obtain **Results** a highly chaotic trajectory (Lyapunov value: 3.18 nats/sec) recorded at 240 fps was used to replace the GLS neuron in the Neurochaos feature extraction algorithm of the ChaosNet NL architecture [1]. This was run in a high training sample regime: 80%-20% train-test split and 5-fold cross validation. The hyperparameter ϵ was tuned in the range of 0.0 and 0.5 (step-size $=$ 0.001) to find the value at which the macro F1 score is highest. We compare the classification performance between the GLS-neuron [2] and the Double Pendulum (DP) based NL architectures (Table 1) for the 8 datasets.

Table 2: GLS vs. Double Pendulum based Neurochaos Learning – Best Macro F1-scores and corresponding tuned hyperparameter ϵ for classification tasks on 8 datasets.

Dataset	**GLS F1**	**DP F1**	**Tuned ϵ**
Iris	1.000	0.895	0.500
Ionosphere	0.860	0.848	0.482
Wine	0.976	0.952	0.159
Bank Note	0.845	0.813	0.500
Haberman's Survival	0.560	0.621	0.167
Breast Cancer	0.927	0.982	0.356
Statlog (Heart)	0.738	0.862	0.164
Seeds	0.845	0.853	0.221

From Table 1, we infer that physical source of chaos (the Double Pendulum trajectory) for Neurochaos Learning architecture yields comparable (and at times superior) classification performance when compared with mathematical chaos (GLS).

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A Dictionary Based Pattern Entropy Framework for Causal Analysis in Nonlinear Time Series Data

Shubham Bhilare[1], Aditi Kathpalia[2], Nithin Nagaraj[3], Harikrishnan N B[1]

[1]Department of Computer Science and Information Systems, BITS Pilani K K Birla Goa Campus, NH 17B, Bypass Road, Zuarinagar, 403726, Goa, India, harikrishnannb@goa.bits-pilani.ac.in, 2025proj022@goa.bits-pilani.ac.in
[2]Department of Applied Mechanics and Biomedical Engineering, Indian Institute of Technology Madras, IIT P.O., Chennai 600036, India, aditi@iitm.ac.in
[3]Complex Systems Programme, National Institute of Advanced Studies, IISc Campus, Bengaluru, 560012, Karnataka, India, nithin@nias.res.in

Inferring causal direction in nonlinear and symbolic time-series remains fundamentally challenging due to unknown generative mechanisms, the absence of parametric models, and the sensitivity of existing methods to noise, delay, and finite samples. Recently, Dictionary based Pattern Entropy (DPE), an in-house developed novel framework for causal inference, was introduced in the paper [1]. DPE is based on the principles of Algorithmic Information Theory and Shannon's Information Theory. In this research, we evaluate the efficacy of DPE in linear (coupled autoregressive processes AR(1)), nonlinear (coupled chaotic maps), and symbolic sequences (delayed bit-flip dynamics with diverse delays and noise levels). In the synthetic AR(1) coupling processes, DPE achieves accuracy exceeding 99% for coupling coefficients greater than 0.4. In 1D coupled skew-tent maps, DPE achieves 100% accuracy in all coupling strengths (except $\phi = 0$) as illustrated in Figure 1. In contrast, Transfer Entropy (TE) and Granger Causality (GC) fail to capture the true direction of causation. DPE consistently shows higher accuracy under delayed bit-flips (accuracy $> 97\%$ up to a delay of 6 bits). While the performance of TE decreases, GC remains inconsistent. DPE shows higher accuracy (accuracy in the range 80% to 100%) even when noise levels increase from 0% to 20%. DPE achieves competitive and often superior performance relative to TE and GC.

The behavior of the coupled skew-tent maps is illustrated in Figure 1. The map function $T(x, b)$ is a piecewise linear chaotic map defined as:

$$T(x,b) = \begin{cases} \frac{x}{b} & \text{if } 0 \le x < b \\ \frac{1-x}{1-b} & \text{if } b \le x < 1 \end{cases}$$

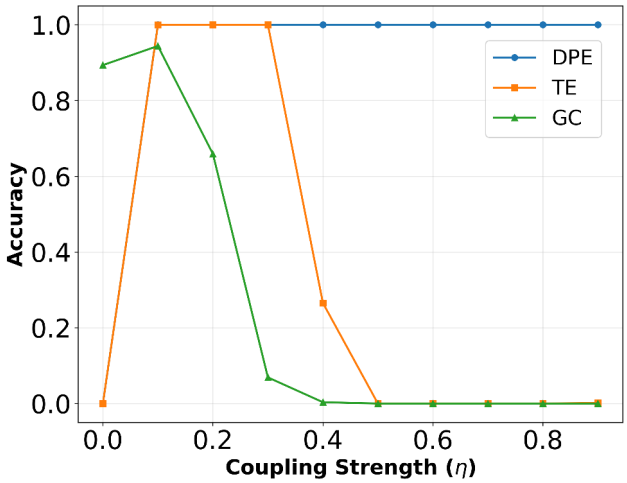

Figure 1: Coupled 1D skew-tent maps: accuracy of DPE, TC, and GC across varying coupling (η) strengths.

The governing equations used to generate the driver (D_t) and response (R_t) time series follow a unidirectional coupling scheme:

$$D_t = T_1(D_{t-1}, b_1)$$

$$R_t = (1-\eta)\, T_2(R_{t-1}, b_2) + \eta D_t$$

The skewness parameters of the maps are fixed at $b_1 = 0.35$ for the D_t and $b_2 = 0.76$ for the R_t. The coupling coefficient η is varied from 0.0 to 0.9 in increments of 0.1.

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Influence Dynamics in Cryptocurrency Networks

Shubhangam Shukla, Mahesh Peyyala and Abhijit Chakraborty

Indian Institute of Science Education and Research Tirupati, Andhra Pradesh, India - 517619

Cryptocurrencies are rapidly gaining global prominence as individuals and institutions alike recognize their potential for decentralized finance, investment opportunities, and cross-border transactions. A wealth of cryptocurrency trade data is now accessible through exchanges, financial data providers, and blockchain explorers, offering both real-time and historical insights into prices, volumes, and transaction flows. This abundance of data has sparked growing academic interest, with researchers investigating market dynamics, mechanisms of price formation, and patterns of investor behavior in decentralized financial ecosystems. Recent studies, for example, have examined the effects of information flows in cryptocurrency markets using the Granger causality framework [1]. Building on this line of work, we delve deeper into the degree of price influence among cryptocurrencies and the evolution of their underlying networks.

We constructed networks of cryptocurrencies, where the nodes correspond to individual cryptocurrencies and the links are determined by measuring the Granger causality (GC) among their price fluctuations within weekly time windows. Price fluctuations were captured through logarithmic returns. The dataset was obtained from the Kraken cryptocurrency exchange and consists of traded price data. Prices were aggregated at a one-minute resolution using the volume-weighted average price to represent the minute-level price, while the total trade volume was recorded as the sum of all transactions within that minute. For minutes without trades, the last available price was carried forward to maintain time-series continuity, with the trade volume set to zero. The logarithmic return of each price series was computed as $r(t) = \log P(t + \Delta t) - \log P(t)$, where $P(t)$ is the price of the cryptocurrency in USD at time t and $\Delta t = 1$ minute. To construct the network, we applied the Granger causality method, which establishes a directed link from a source to a target if the past information of the source improves predictions of the target beyond what the target's own past provides. A link between two nodes was included only when the GC strength exceeded a significance threshold of 1%. Consequently, the resulting networks are both directed and weighted. The weight represents the strength of Granger causality between two log-return time series [1, 2]. Our analysis covers the period from January 2020 to March 2025, dividing the data into successive weekly networks. The number of nodes grows steadily over time, rising from 30 in the first week of 2020 to 390 by the final week of March 2025.

The link-weight distributions in the weekly cryptocurrency network are heterogeneous. The overall influence of a cryptocurrency is quantified by its out-strength. Ranking cryptocurrencies [Fig. 1 (left)] by their average quarterly out-strength reveals that Ethereum (ETH) consistently emerges as the most stable and influential cryptocurrency throughout 2020–2025. By contrast, Bitcoin (XBT) shows a gradual decline in influence during this period. Moreover, between q3 2022 and q1 2025, the rankings of influential cryptocurrencies display considerable instability. Notably, 17 different cryptocurrencies appeared at least once in the top-five influential list over the five-year span. To better understand the drivers of this influence, we examined the relationship between out-strength and the weekly log returns of cryptocurrencies. The scatter plot in Fig. 1 (right) reveals a statistically significant *negative* correlation (Pearson $r = -0.2972$, $p = 5.44 \times 10^{-7}$). A similar negative correlation is observed across other cryptocurrencies as well. In contrast, stable coins do not exhibit such a relationship between out-strength and weekly log returns. This suggests that during periods of price decline, cryptocurrencies exert a stronger influence on the price dynamics of other cryptocurrencies. We examine the overall evolution of the network during this period through an analysis of its graph spectra. The significance of the observed spectra is assessed by comparison with a randomized counterpart generated by reshuffling the log-return time series. In addition, we investigate the temporal evolution of cryptocurrency clusters.

Our findings highlight the dynamic and heterogeneous nature of influence among cryptocurrencies. While Ethereum remains the most stable and dominant player, Bitcoin shows a steady decline in influence, with significant ranking fluctuations across other assets. These results provide new insights into the structural evolution and clustering behavior of cryptocurrency networks in a volatile market.

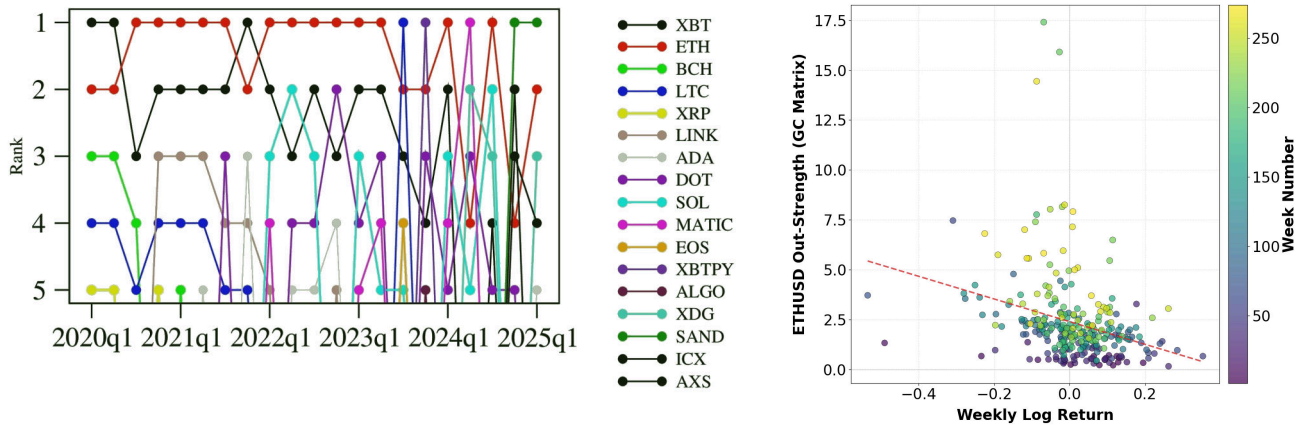

Figure 1: (Left) Temporal evolution of the top five most influential cryptocurrencies. (right) Out-strength versus weekly log returns for ETH.

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Double step transition and multistability in Kuramoto oscillators with higher order interactions

Sidharth Pradhan[1], **Sangeeta Rani Ujjwal**[1]

[1]Institute of Science, Banaras Hindu University-221005
sidharthpradhan03@bhu.ac.in

We investigate a variant of the Kuramoto model incorporating both pairwise and higher order interactions, where the couplings can be either positive (attractive) or negative (repulsive). In this framework, oscillator phases can be interpreted as opinions, and the pairwise interactions (attitudes) between agents are determined by the distance between their respective opinions. These pairwise attitudes are further extended to define higher order (triadic) interactions within the system. Our analysis reveals the emergence of multistability, characterized by a double step transition. We systematically examine the influence of both dyadic and triadic interaction strengths on the stability and range of these multistable states. Furthermore, the inclusion of higher order interactions provides insight into the role of tripartite relationships among agents in shaping the formation and structure of opinion clusters.

Dynamics and Bifurcation of Natural Circulation Loop through Numerical Continuation

Dinabandhu Rout[1], Sirshendu Mondal[1], Aranyak Chakravarty[2], Koushik Ghosh[2], Achintya Mukhopadhyay[2]

[1]National Institute of Technology Durgapur, Durgapur, India
[2]Jadavpur University, Kolkata, India

A natural circulation loop (NCL) is a closed fluid circuit consisting of a heater, a cooler, and connecting pipes, where fluid motion is driven solely by buoyancy forces arising from temperature-induced density differences. NCLs are used in systems such as nuclear reactors, solar water heaters, and cooling circuits to enable passive heat transfer without external pumps, thereby enhancing safety and energy efficiency [1]. However, NCL can become unstable under certain operating conditions, causing oscillatory flow and temperature fluctuations. This instability motivates bifurcation and stability analysis to predict and control such oscillatory behavior.

A mathematical model developed by Fichera *et al.* [2] of a single-phase rectangular NCL is adopted. Here, the Fourier series expansion is used to convert the governing PDEs (momentum and energy conservation) to a system of ODEs. In the present study, bifurcation analysis of the NCL system is performed using the numerical continuation toolbox, MatCont. Further, the stability diagrams are drawn by varying a geometric parameter (pipe radius, r or loop height, L) along with the heater power (P).

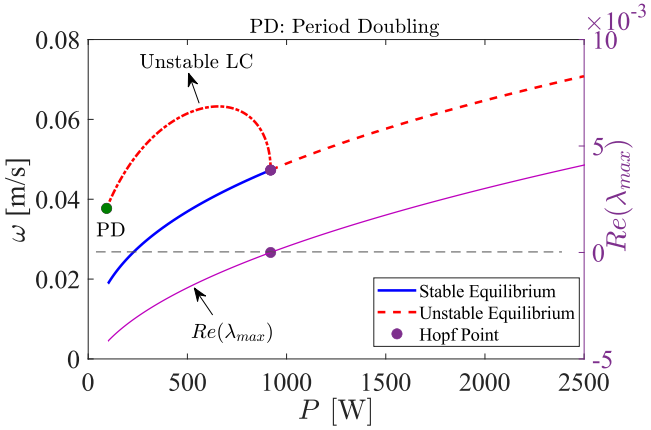

Figure 1: Equilibrium and Limit cycle continuation indicating a subcritical Hopf bifurcation

Figure 1 shows equilibrium (EQ) and limit cycle (LC) continuation in terms of flow velocity (ω), considering heater power (P) as the bifurcation parameter. The stable equilibrium branch indicates a steady flow of the loop fluid. It transitions to an unstable EQ branch through Hopf bifurcation (P = 919.6 W) as the real part of one of the eigenvalues (λ_{max}) becomes positive (Fig. 1). Upon continuation of limit cycles from the Hopf point, an unstable limit cycle branch emerges. The positive first Lyapunov coefficient (≈3.08e-4) confirms that the Hopf bifurcation is subcritical in nature. However, the post-bifurcation dynamics are governed by a distant chaotic attractor (not shown).

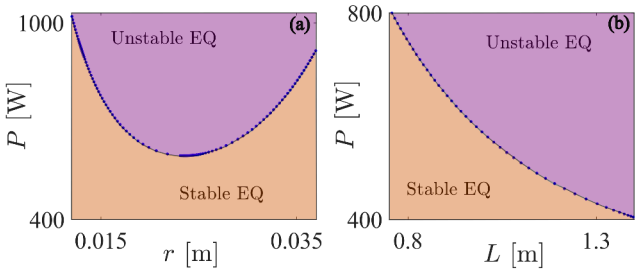

Figure 2: Stability diagram between heater power (P) and a geometric parameter: (**a**) pipe radius, r and (**b**) loop height, L

The stability diagram (Fig. 2) shows regimes of stable and unstable equilibrium (EQ) regions, separated by a Hopf bifurcation curve. For the design of an NCL, the stability diagram serves as a valuable tool for identifying stable operating regimes over a given range of heater power.

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Dynamic characterization of Coupled Natural Circulation Loop (CNCL)

SK Hasan Raja[1], Sudipta Saha[2], Aranyak Chakravarty[2], Sourav Sarkar[1], Achintya Mukhopadhyay[1], Sirshendu Mondal[3], Koushik Ghosh[1]

[1]Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India
[2]School of Nuclear Studies and Application, Jadavpur University (Salt Lake Campus), Kolkata 700106, India
[3]Department of Mechanical Engineering, NIT Durgapur, Durgapur 713209, India

Natural circulation loops (NCLs) are widely used in nuclear reactors for passive decay heat removal, driven by buoyancy forces arising from temperature-dependent density gradients. Despite their simplicity, these systems exhibit nonlinear thermo-hydraulic behavior and are prone to instabilities such as Kelvin–Helmholtz, flashing, and Ledinegg. In this study, a lab-scale coupled NCL setup (Fig. 1) is developed, where the primary loop includes a bottom-mounted heater simulating the reactor core and is thermally coupled to a secondary loop through a common heat exchanger, with heat rejection via a cooler. The heating power input is systematically controlled to investigate system dynamics.

The plots illustrate the coupled thermo-hydraulic behavior of the natural circulation loop system. The flow signal initially remains steady with minimal fluctuations, but transitions to a strongly oscillatory regime upon heating, exhibiting sustained high-amplitude fluctuations of mass flux indicative of thermo-hydraulic instability arising from nonlinear interaction between buoyancy and flow resistance. At later times, increased oscillation amplitude suggests a shift toward a more unstable regime. Correspondingly, temperature measurements across multiple locations show a rapid rise from ambient conditions followed by a gradual approach to steady state, with higher temperatures near the heater and heat exchanger compared to other regions. The variation in temperature levels and response times indicates strong spatial non-uniformity and inter-loop coupling, while small fluctuations near steady state suggest the persistence of weak oscillatory behavior under continuous heating.

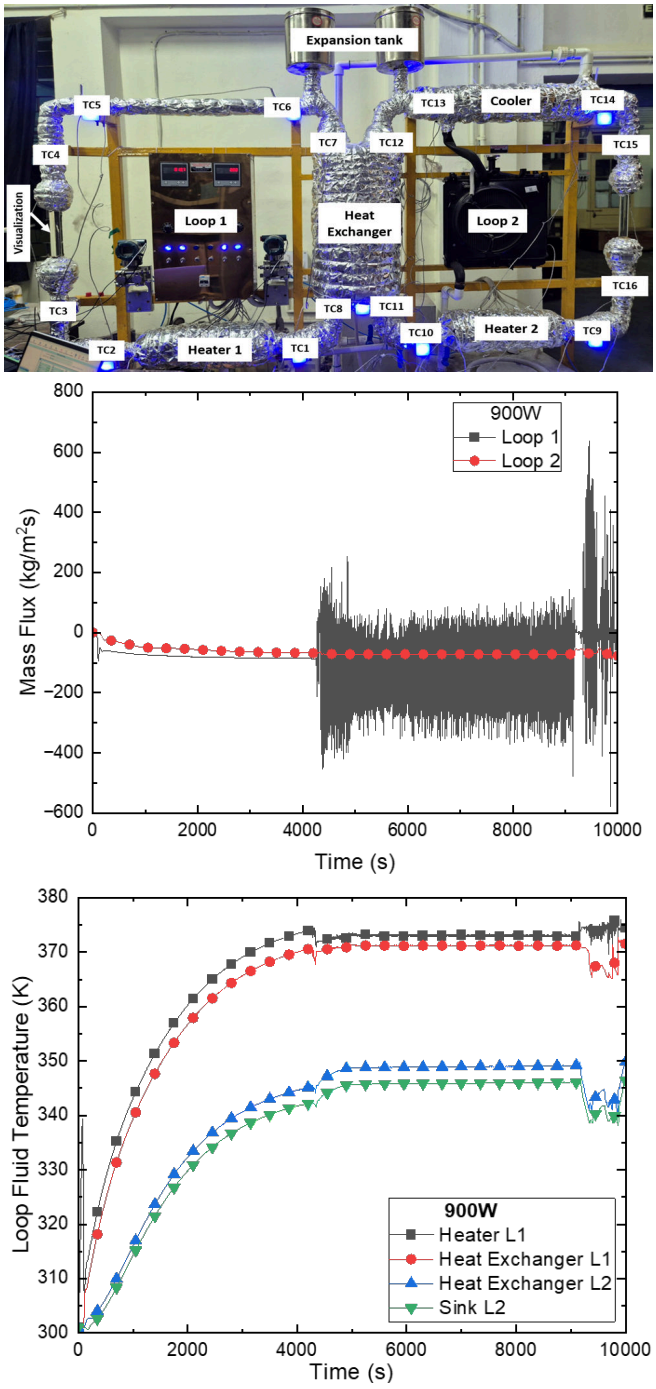

Figure 1: Experimental set-up (top), Temporal variation of mass flux (middle) and Temperature of different locations (bottom) at 900W

Emergent Metastability in Random Geometric Networks with Higher-Order Interactions

Soorya P P[1], Biswambhar Rakshit[1]

[1]Department of Mathematics, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham,Tamilnadu,India

Metastability, a key feature of brain dynamics, is a state that allows neural systems to flexibly transition between partially synchronized configurations. Although higher-order interactions have been extensively studied using simplicial complexes and and hypergraphs, here we adopt a different approach by modeling effective higher-order interactions through distance dependent connectivity motivated by glial mediated neuronal modulation[**?**]. However, their role in spatially embedded networks reflecting realistic brain connectivity remains unclear. In this work, we examine how distance-dependent connectivity and effective higher-order interactions shape metastable dynamics on a random geometric network, providing a step towards a simplified model of neuro-glial networks.

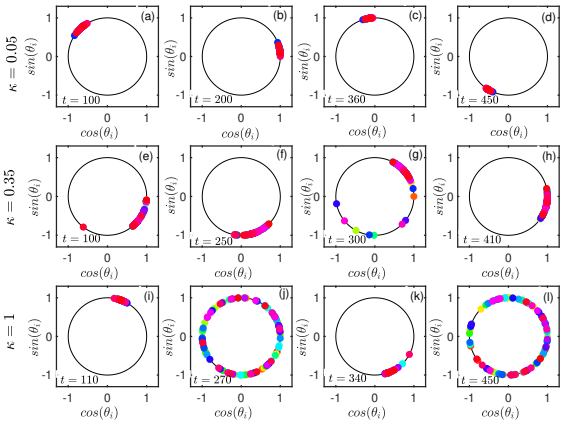

Figure 1: Snapshots of instantaneous phase distribution of all neurons at different coupling strengths: (a-d) $\kappa = 0.05$, (e-h) $\kappa = 0.35$, and (i-l) $\kappa = 1$.

We consider a network of N Izhikevich neurons in a 2D square domain (100×100) with distance-dependent Waxman connectivity $p_{ij} = p_0 e^{-(\frac{s_{ij}}{\beta L})}$, where p_0 is the maximum connection probability, s_{ij} the Euclidean distance between neurons i and j, β the spatial decay parameter that controlling connection range, and L the maximum possible distance within the domain[**?**]. The neuronal dynamics are governed by

$$\dot{v}_i = 0.04v_i^2 + 5v_i + 140 - u_i + I_i, \quad \dot{u}_i = a(bv_i - u_i)$$

with after-spike reset $v_i \geq 30$ mV: $v_i \leftarrow c$, $u_i \leftarrow u_i + d$. The synaptic input to neuron i is

$$I_i(t) = I_i^{dc} + \sum_{d=1}^{D} d^{-\alpha} \sum_{j \,|\, d_{ij}=d} I_{ij},$$

where I_i^{dc} is external input, d_{ij} is the topological distance, and $I_{ij} = \frac{k}{\sigma}[e^{-2(t-t_j)}(V_0 - V_i)]$, represents the synaptic contribution. V_0 is the excitatory reversal potential, and synaptic conductance k is normalized by the node degree σ. In this framework, the input current to neuron i receives contributions from neurons located at different topological distance d.

The results reveal rich collective dynamics under effective higher-order interactions, whereas purely pairwise coupling $D = 1$ leads to fully synchronized spiking and bursting. In contrast, Higher-order interactions $D = 2$ induce partially synchronized states with temporal fluctuations and the intermittent formation and dissolution of coherent clusters (Fig. 1), characteristics of metastability.

The metastability index σ_R quantifies persistent variability in the degree of synchronization, confirming the non-stationary nature of the collective states.

Disease Dynamics Beyond Equilibrium: Environmental Forcing, Rate-Induced Tipping, and Early Warning Signals

Sujit Halder[1], **Joydev Chattopadhyay** [1]

[1]Agricultural and Ecological Research Unit, Indian Statistical Institute, Kolkata-108, 203, B.T.Road, West Bengal, India

Eco-epidemiological dynamics are increasingly influenced by gradual environmental change, yet most theoretical studies assume static parameters. To address this, we develop a framework for disease-mediated predator-prey interactions under environmental forcing by extending the Rosenzweig–MacArthur model with an SI-type infection in the predator population. We begin with a detailed deterministic analysis, employing both one- and two-parameter bifurcation techniques to systematically classify the qualitative dynamical regimes of the system. These include prey-only equilibria, disease-free coexistence states, endemic steady states, and sustained oscillatory dynamics. The transitions between these regimes are primarily organized by variations in key ecological and epidemiological parameters, notably the prey carrying capacity and the disease transmission coefficient.

Subsequently, we generalize the model by allowing these governing parameters to vary explicitly in time, thereby constructing a rate-dependent dynamical system. This extension enables a direct comparison between instantaneous (quasi-static) bifurcation structures and actual system trajectories under finite rates of environmental change. The analysis reveals several nontrivial dynamical phenomena that are not captured in static settings, including delayed bifurcation responses, transient tracking of unstable invariant sets, and rate-induced tipping transitions.

In regimes characterized by sufficiently high disease-induced mortality, the system admits bistability between distinct endemic oscillatory attractors. We quantify the relative resilience of these coexisting states using basin stability measures and further extend this concept to non-autonomous settings by introducing rate-dependent transition probabilities between attractors under time-varying conditions.

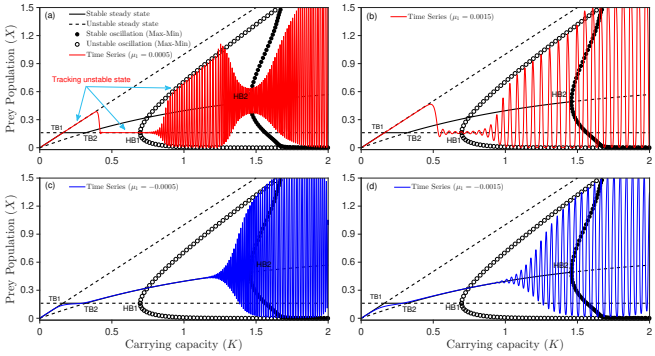

Figure 1: Rate-dependent dynamics: When the carrying capacity varies over time, the system exhibits tracking of unstable states near both transcritical and Hopf bifurcations. For positive rates (and similarly under decreasing environmental change), trajectories closely follow the stable branches of the bifurcation structure. Stable equilibria are shown as solid black curves (dashed for unstable), while rate-dependent trajectories are depicted in red (increasing) and blue (decreasing) curves.

To evaluate invasion in a nonstationary environment, we introduce a rate-dependent reproduction number and an associated transition timescale, providing a dynamic analogue of the basic reproduction number. Incorporating environmental stochasticity, we compute early warning signals from stochastic trajectories to detect impending critical transitions. Overall, integrating rate-dependent modeling, bifurcation analysis, and early warning theory offers a robust framework for anticipating disease-driven regime shifts under gradual environmental change.

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Exploring soliton propagation in an optical fiber using Lax pair-informed neural network

G Sujitha[1], P. Ramesh Babu[1,*], K. Senthilnathan[1]

[1]Photonics Research Lab, Department of Physics, School of Advanced Sciences, Vellore Institute of Technology, Vellore, India, 632014

Neural networks, one of the deep learning (DL) techniques, translate the complex process of solving nonlinear partial differential equations (PDEs) into an optimization problem. Rather than entirely depending on data, introducing the physics information of the system as constraints into the DL algorithm named Physics-informed neural network (PINN) makes the results more accurate and reliable [2]. Lax pair is one of the features of the integrable systems [3]. Introducing it as a physics constraint into the network called Lax pair-informed neural network (LPNN) simplifies the task of solving a nonlinear PDE. It converts a nonlinear PDE into a pair of linear differential equations i.e. spectral problems [1] given by,

$$\phi_x = M\phi$$
$$\phi_t = N\phi$$

where M and N are lax pair and ϕ is the spectral function. LPNN is backed up by a rigorous mathematical structure that helps with the interpretability of the results compared to the standard PINN [1]. The lax pair, the zero-curvature condition

$$M_t - N_x + [M, N] = 0$$

, along with the initial and boundary conditions of the system form the physics-informed part of the LPNN.

The nonlinear Schrödinger equation (NLS) governs the pulse propagation through optical fibers. The effects of dispersion and nonlinearity cancel out each other, leading to the formation of an optical pulse without any distortion in both spectral and temporal domains that facilitate lossless propagation through the fiber called a soliton.

In this work, we compute the fundamental soliton and breather solutions of the NLS using Lax pair-informed neural network and compare the results with the standard PINN architecture. The governing equation of pulse propagation is given by,

$$iq_t + \frac{1}{2}q_{xx} + |q|^2 q = 0$$

where q is the slowly varying field. The neural network has spatial and time variables as the inputs. It comprises of five hidden layers of 100 neurons per layer. The hyperbolic tangent function is the activation function used in the feed-forward neural network. The initial and boundary conditions are given by,

$$[q(x,t)]\,\big|_{t=0} = q(x),\ x \in \Omega$$
$$[q(x,t)]\,\big|_{x\in\partial\Omega} = q(t),\ t \in [0,t]$$

where x,t are spatial and time variables respectively. Ω and $\partial\Omega$ represent the spatial variable range and the boundary of the domain respectively. 100 data points are randomly sampled for initial and boundary data and 10,000 collocation points are sampled by the latin hypercube sampling (LHS) technique from the spatiotemporal domain for uniform distribution. The network computes the solution of the considered nonlinear PDE and associated spectral functions. The spectral parameter is treated as a learnable parameter of the network. The automatic differentiation bridges the neural architecture and the physics informed part. The loss function is formulated as the sum of initial and boundary loss, residual loss from Lax pair and the zero-curvature condition. The loss function is optimized through back propagation by using limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) algorithm.

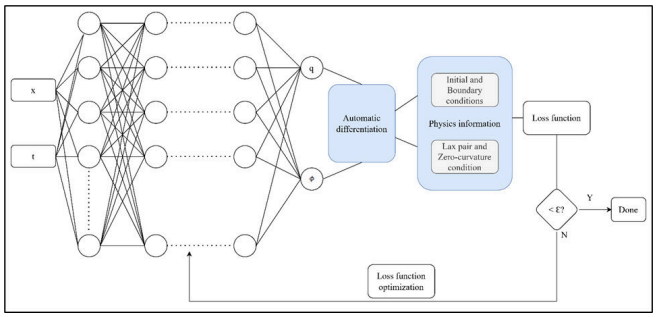

Figure 1: Figure 1: Schematics of LPNN

The LPNN is expected to show higher training accuracy with low relative Euclidean norm error and less computing time compared to standard PINN architecture.

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Chaos and Noise-Induced Oscillations in a Nonlinear Y-Branch Mechanical System

Sukruta A. Pethe[1,2], Adwait A. Kulkarni[1], Kiran M. Kolwankar[1]

[1]Department of Physics, Ramniranjan Jhunjhunwala College, Ghatkopar, Mumbai 400086, India
[2]Department of Physics, Sathaye College, Vileparle (East), Mumbai 400057, India

In this work, we study the nonlinear dynamics of a Y-shaped mechanical system under directional wind forcing. The model includes gravitational effects, nonlinear restoring forces, damping, and forcing applied both along and perpendicular to the plane of the structure [1, 2].

From numerical simulations, we observe, as expected, that as the system parameters are varied, the behavior changes from periodic to irregular motion. In order to quantify this, we compute the maximum Lyapunov exponent and identify parameter ranges where chaotic behavior is observed. Phase space analysis also shows sensitive dependence on initial conditions. We also study the effect of stochastic perturbations in the forcing. For constant forcing, the system shows damped oscillations in simulations. However, experiments show sustained oscillatory motion under similar conditions. By adding small noise in the forcing term, recover the sustained oscillations. This helps in explaining the difference between simulation and experimental observations.

Overall, this work is a step towards understanding of the nonlinear behavior of branched systems and demonstrates the important role played by noise in the realistic modeling of wind-driven structures.

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Dynamic and Irreversible Cell Shape Changes through Mechanochemical Coupling during Morphogenesis

Suman Halder, Arkayan Laha & Rumi De

Department of Physical Sciences, Indian Institute of Science Education and Research Kolkata, Mohanpur 741246, West Bengal, India

Cell shape changes are fundamental to numerous biological processes, including embryonic development, tissue morphogenesis, wound healing, and cancer progression. These morphological transformations arise from the interplay of cytoskeletal dynamics, actomyosin contractility, and mechanical forces that regulate cellular structure and responsiveness to external stimuli. Mechanical strain can influence cytoskeletal remodeling and thereby alter the dynamics of cellular deformation. Here, we present a theoretical model that incorporates nonlinear cellular elasticity together with substrate mechanosensing. Our theory provides a physiologically relevant description of cell shape regulation, allowing both reversible oscillatory deformations and irreversible morphological transitions to emerge spontaneously from the system dynamics. By combining nonlinear elasticity, active contractility, and substrate viscoelasticity, the framework captures key mechanisms underlying diverse cellular shape transformations. Such dynamics can help explain behaviours as observed in experiments, including oscillatory deformations during the development of Drosophila embryos [1] and permanent shape changes reported in lung epithelial cells and fibroblasts [2]. These results highlight how the interplay between biochemical activity and mechanical feedback regulates cellular morphogenesis. Our findings further suggest that this coupling plays an important role in adaptive cellular shape remodeling and tissue morphogenesis.

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Nonlinear Wave Propagation and Shock Formation predictions in Urban Floods via Characteristic Surfaces

Sridevi Priya M[1] and P.P.Mujumdar[1]

[1] Department of Civil Engineering, Indian Institute of Science, Bengaluru, India

The Shallow Water Equations(SWE)-classified as a nonlinear hyperbolic system governing wave propagation in catchment flood dynamics-simplify into kinematic wave equations(a specialized class of quasi-linear form) by neglecting forces and acceleration terms :

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_0 - \alpha \frac{1}{w}\frac{dw}{dx} h^m$$

where h is the height of water; q is the discharge per unit width; i_0 is the rainfall excess; t is the time; x is the downslope length; α is the surface roughness; and w is the width of domain.

Analysing these quasi-linear forms is a critical prerequisite for real-time fluvial modelling, as they retain essential SWE features while ensuring computational efficiency and numerical stability. Intrinsic nonlinearity causes smooth solutions to undergo a "gradient catastrophe", physically representing the steepening of shock fronts as flood waves move downstream. While these dynamics can be visualized via characteristic surfaces as solutions for the equations in the x-t plane, such propagation mechanisms remain unexamined within Indian urban catchments.

This study investigates characteristic surfaces as an intrinsic framework for hyperbolic equations to model flood wave propagation. By deriving discharge hydrographs directly from characteristic curves, this approach mathematically explains shock formation and its impact on the outlet hydrograph, thereby linking wave physics to the time of concentration and peak discharge.

The characteristic surfaces contain curves that can be expressed by a class of special functions such as Gamma,Beta, and Hypergeometric functions[1]. Among these functions, the Hypergeometric functions established by Lapides et al.[2],were found to effectively integrate the effects of the complex domain in closed-form solutions and, therefore, were used in this work. Figure 1 illustrates the mapping of characteristic path curve onto the outlet hydrograph by those functions.

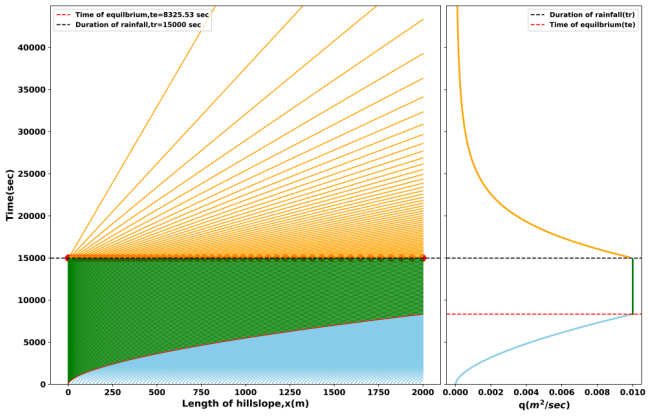

Figure 1: Mapping the characteristic paths of wave propagation (in x-t plane) to the outlet hydrograph(q-t plane).The Characteristic curves (left) for a planar hillslope(L = 2000 m, slope =0.01, Manning's coefficient=0.05,i_0= 18 mm/hr) under turbulent flow conditions are shown alongside the corresponding hydrograph (right).

From these characteristic curves, the outlet hydrograph containing the peak discharge and time to peak is calculated for the flood analysis of the plain domain. In the full paper, this framework will be extended to study: 1) converging and diverging domains, 2) Kinematic shock formation and how it affects the hydrograph, and 3) the steepening of flood waves. Overall, the framework developed in this study will be used to construct accurate and stable numerical schemes for the real-time modelling of urban floods using the full dynamic shallow water equations.

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Transitions from Frequency Chimera to Oscillation Death and Chimera Death in a Ring of Coupled Rössler Oscillators

Sunilkumar P.[1,2], **V. Resmi**[1,2]

[1]PTM Government College (affiliated to University of Calicut), Perinthalmanna 679322, Kerala, India
[2]Government Victoria College (affiliated to University of Calicut), Palakkad 678001, Kerala, India

Chimera states are spatiotemporal patterns in coupled oscillations networks where coherent and incoherent domains coexist. Originally discovered in non locally coupled phase oscillators, they have since been observed for local and global coupling, in one, two and three dimensional geometries, and across single and multilayer networks. Related emergent behavious in coupled oscillators include synchronization, amplitude mediated chimeras, oscillation death, chimera death and amplitude death.[1]

In our study, we consider a ring of Rössler systems with diffusive coupling, where each node evolves according to the following equations.

$$\dot{x}_i = \tau_i(-y_i - z_i) + \frac{\tau_i \epsilon}{2P} \sum_{j=i-P}^{i+P} (x_j - x_i),$$
$$\dot{y}_i = \tau_i(x_i + a y_i),$$
$$\dot{z}_i = \tau_i(b + z_i(x_i - c)).$$

with periodic boundary conditions.The parameter τ_i controls the time scale of each oscillator and ϵ denotes the coupling strength. Oscillators with $\tau_i = 1$ evolve on a fast time scale, while oscillators with $\tau_i < 1$ evolve more slowly. The coupling range P is varied from strictly local ($P = 1$) to global ($P = N/2$). We consider $N = 100$ Rössler systems with $N_s = 50$ on a slow time scale distributed randomly in a ring. We obtain frequency chimera states under local coupling for values of $\epsilon = 0.7$ and $\tau_i = 0.76$, in agreement with earlier reports [2]. We now study the effect of changing the coupling range. When we increase P, we observe oscillation death for intermediate values of P, and chimera death for large values of P.

To characterize synchronized states and chimera, we employ the strength of incoherence S_f[3]. In fig. 1, we show S_f, in the parameter plane $\epsilon - P$. We fix the τ_i for slow systems to be $\tau_i = 0.76$ and vary ϵ and P. For each value of (P, ϵ) we plot S_f in a color scale. The color scale represents the strength of incoherence S_f: darker shades (small S_f) indicate coherent states, while bright yellow regions (large $S_f \approx 1$) correspond to strongly incoherent dynamics.

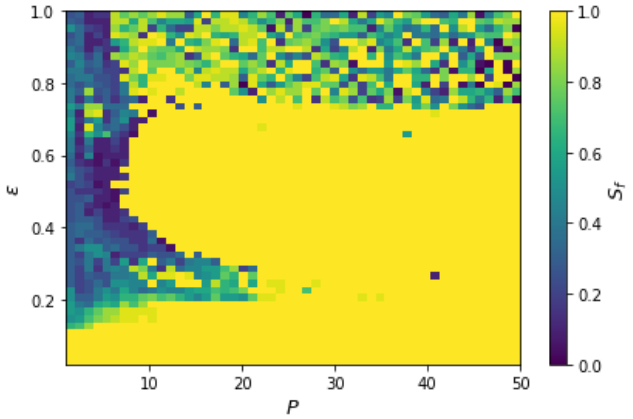

Figure 1: $S(f)$ in the parameter plane $P - \epsilon$. The color scale represents S_f. $S_f = 0$ corresponds to frequency coherence, $S_f = 1$ incoherence or oscillation death, and intermediate values $0 < S_f < 1$ signal chimera-like configurations. Other parameters are $N = 100$, $N_s = 50$, $\tau_i = 0.76$ for slow systems. Rössler parameters are $a = b = 0.1$ and $c = 18$ for chaotic regime.

Thus we find that coupling range is an important parameter for the emergent behaviour in complex oscillator networks.

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Experimental Verification of Spectral Signatures of Bifurcations

Suvradip Maity[1], Debajyoti Guha[2], Soumitro Banerjee[1]

[1]IISER Kolkata, India
[2]Swami Vivekananda University, Kolkata, India

Bifurcation theory provides a fundamental framework for understanding qualitative transitions in nonlinear dynamical systems. While traditional approaches rely on phase-space reconstruction and bifurcation diagrams, spectral analysis of time-series data has recently emerged as an efficient alternative, leading to the concept of spectral bifurcation diagrams (SBDs) [1], where distinct spectral patterns characterise different dynamical regimes.

In this work, we develop an experimental methodology to realize spectral bifurcation diagrams in physical systems. Nonlinear electronic circuits are used to emulate dynamical systems, with system parameters controlled by voltage inputs from a data acquisition (DAQ) interface. The DAQ, controlled via Python, enables automated parameter sweeping [2] and simultaneous acquisition of time-series data. The acquired time-series is processed using FFT for each parameter value, and the dominant frequencies are plotted as a function of the control parameter to obtain the SBD.

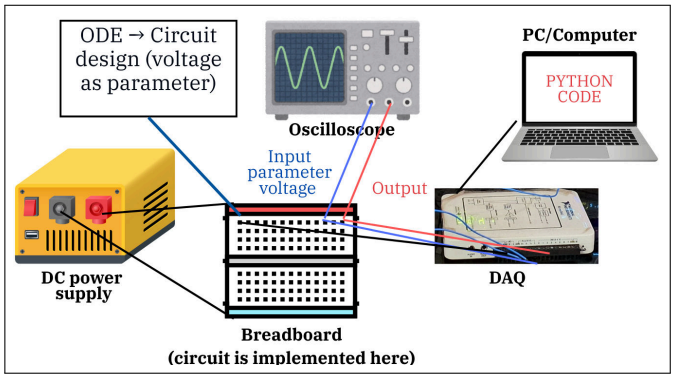

Figure 1: Schematic of the experimental setup

The proposed framework is validated on systems such as the Rössler oscillator and quasi-periodic oscillators. In the Rössler system, the spectral bifurcation diagram captures the period-doubling cascade leading to chaos via successive frequency halvings, eventually yielding broadband spectra indicative of chaos. In quasi-periodic regimes, the emergence of incommensurate frequencies and their combinations is observed as cross-hatching patterns.

The governing equations used to construct the circuit for quasi-periodic oscillations are given by [3]

$$\begin{aligned} \ddot{x} - (\lambda + z + x^2 - \beta x^4)\dot{x} + \omega_0^2 x = 0 \\ \dot{z} = b(\varepsilon - z) - k\dot{x}^2 \end{aligned} \tag{1}$$

Distinct spectral patterns are also observed in torus doubling and three-frequency quasi-periodicity.

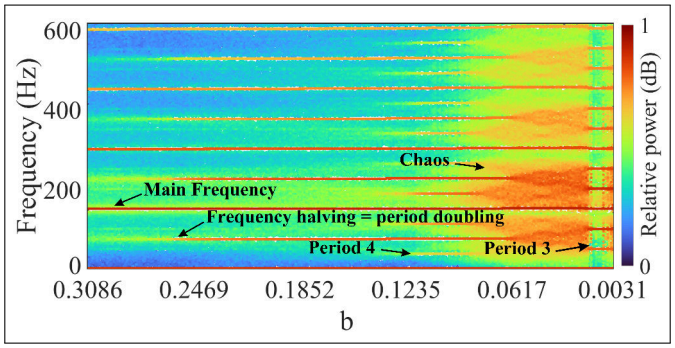

Figure 2: SBD of Rössler system

The experimentally obtained SBDs successfully reproduce the characteristic spectral signatures reported in numerical studies [1].

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Closed form exact solitary wave solutions of KdV equation with higher order nonlinearities

Jatavath Suresh[1], **Thokala Soloman Raju**[1]

[1]Department of Physics, Faculty of Science and Technology, ICFAI Foundation for Higher Education Dontanapally, Hyderabad 501203, Telangana, India

It is an established fact that the Korteweg-de Vries (KdV) equation is a fundamental component in nonlinear science, renowned for its extensive applications across a variety of physical properties. Of the several applications of this equation, the most important ones are to one-dimensional nonlinear lattice, fluid mechanics, quantum mechanics, plasma physics, nonlinear optics, and more.

Additionally, the KdV equation can explain such interesting phenomena as nonlinear long internal waves that signify the flow of internal localized waves—each moving with different densities. Long developed a time-independent form of this equation, and Benney put forward an integral representation of its coefficients for waves in arbitrarily stratified fluids. Also Kivshar and Malomed examined coupled KdV equations that mimic the waves in a fluid that has different layers or densities and experience gravity's influence.

Higher order nonlinear Korteweg-de Vries equation (HKdV) [1] aptly describes wave motion in one-dimensional nonlinear lattice and plasma physics. This work presents a variant of KdV equation with higher-order nonlinearities that signify the flow of internal localized waves, each moving with different densities and subjected to a free surface. Such phenomena commonly encountered in plasma systems such as ion-acoustic waves, magnetosonic structures, and dusty plasma oscillations. By using an elegant transformation, we discover bright, dark, and kink solutions [2] to this HKdV with higher order nonlinearities, in closed form. Toward the end we performed numerical simulations using finite-difference numerical scheme to check the stability of these solutions against finite perturbations. Our results not only contribute new mathematical insights but also open up potential applications in plasma physics, where controlled manipulation of nonlinear wave phenomena is essential—for instance, in space plasmas, fusion devices, and plasma-based communication systems

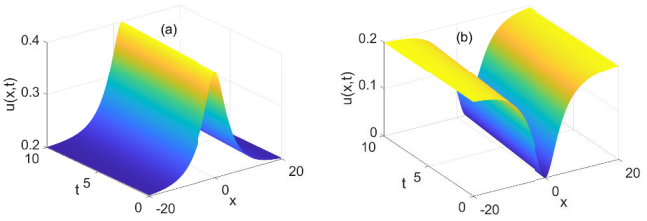

Figure 1: (a) Surface plot depicting a bright soliton for $A = 0.2$ and $B = 0.2$. and (b) surface plot depicting a dark soliton for $A = 0.2$ and $B = -0.2$.

In Fig.1 we depict the bright and dark solitary wave solutions of this HKDV for different amplitude parameters as described in the figure caption. We emphasize that these are the exact solutions in closed form expression for this HKDV.

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Dynamics of Walking Droplets in a Piecewise Smooth Potential

Titir Mukherjee[1], Rahil Valani[2], Soumitro Banerjee[1]

[1]Indian Institute of Science Education and Research Kolkata, Mohanpur, India
[2]University of Oxford, Oxford, UK

Walking droplets, or "walkers," are macroscopic wave-particle entities that emerge when droplets bounce on a vertically vibrated fluid bath [1]. These systems exhibit a range of quantum-like behaviors, including wave-particle duality, tunneling, and orbit quantization, making them compelling hydrodynamic analogues of quantum systems [2].

The walker dynamics is modeled using a memory-driven stroboscopic framework, in which the particle interacts with the wave field generated during its past bounces [1]. This memory effect, characterized by a parameter M, effectively maps the system to a high-dimensional dynamical system that can be reformulated as a Lorenz-like system with forcing [4]. Such dynamics has been previously studied in smooth confining potentials, where multistability and chaos have been reported in the high-memory regime [3].

In this work, we investigate walker dynamics in a piecewise smooth potential. Such systems are known to exhibit distinctive dynamical features, including grazing bifurcations, border-collision bifurcations, and abrupt transitions to chaos that are absent in smooth systems [5]. The potential considered here combines a linear harmonic restoring force with a soft impact wall, and is defined as

$$F(x) = \begin{cases} -kx, & x \leq x_{\text{wall}}, \\ -kx - Ak(x - x_{\text{wall}}), & x > x_{\text{wall}}. \end{cases} \quad (1)$$

In this work, through a systematic exploration of the parameter space in (M, x_{wall}), we observed transitions from fixed points to periodic motion and the emergence of chaos in walker dynamics (see Fig. 1). Interestingly, we observed that the onset of chaos is not governed by the memory parameter M alone, but is also strongly influenced by the stiffness parameter A.

The combination of memory and the non-smooth boundary also gave rise to multistability, where distinct long-term behaviors coexist for the same set of parameters. We found that small variations in the wall position can trigger transitions between these states.

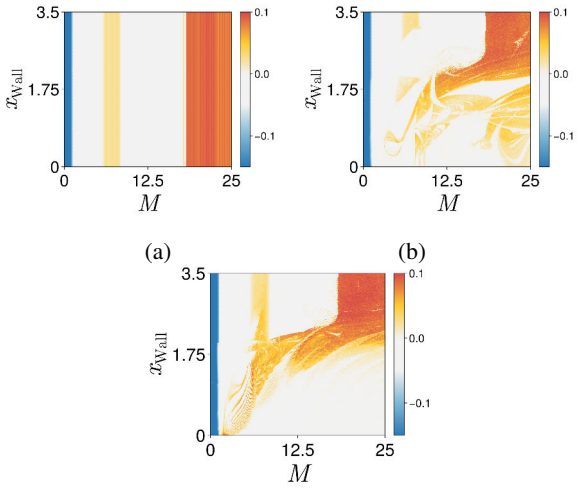

Figure 1: Parameter-space dynamics of the Lyapunov exponent (λ) for varying M and x_{wall} at $A = 0, 5, 100$. Color indicates chaotic ($\lambda > 0$) and periodic ($\lambda \leq 0$) regions, revealing non-smooth bifurcation structures.

These observations establish walking droplets in non-smooth potentials as memory-driven soft-impact oscillators [6], bridging classical impact dynamics with quantum-analogue behavior and suggesting new directions for experimental exploration.

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Nonmonotonic evolution of complexity during transition from chaos to order via strange nonchaotic attractor

Beeraiah Thonti[1,2], Shruti Tandon[1,2], Vedasri Godavarthi[3], Norbert Marwan[4], Jürgen Kurths[4,5], R. I. Sujith[1,2]

[1]Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600 036, India
[2]Centre of Excellence for Studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras, Chennai 600 036, India
[3]Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, United States of America
[4]Potsdam Institute for Climate Impact Research, Potsdam 14412, Germany
[5]Department of Physics, Humboldt University of Berlin, Berlin 12489, Germany

Complex systems often undergo critical transitions from disorder to order, which can have severe consequences. Turbulent reactive flows in gas turbines and rocket engines represent a prominent example, where acoustic pressure fluctuations (p') transition from high-dimensional chaos to order—known as thermoacoustic instability—due to coupling between p' and heat-release fluctuations, potentially leading to catastrophic failure. Despite extensive use of complexity measures, how complexity evolves during such transitions remains unclear, with studies reporting increasing, decreasing, or non-monotonic trends [1].

In our recent work, we reported a metamorphosis in the nature of the transition from smooth to abrupt upon varying a secondary parameter, namely the thermal power input ($\mathcal{P}$) [2]. Here, we investigate how complexity evolves across this metamorphosis of the transition using recurrence analysis of p'. Recurrence plots are constructed with a threshold of a fixed recurrence rate of 2%, and the Shannon entropy of diagonal line length distribution is employed as a measure of dynamical complexity:

$$S = -\sum_{l=l_{min}}^{l_{max}} p(l)\ln p(l)$$

where $l_{min} = 10$ and $p(l)$ denotes the probability of diagonal lines of length l.

A non-monotonic variation of complexity during the transition from disorder to order has been reported in systems such as turbulent combustors [3] and the Ising model [4]. However, these studies do not identify how the complexity peak is associated with specific dynamical states along the transition route. Our results reveal that, across all the types of transitions exhibiting various dynamical routes, complexity consistently evolves in a significant non-monotonic manner only when the route involves a strange nonchaotic attractor (SNA) (refer to Fig. 1). Specifically, complexity decreases initially, then increases to a maximum, and finally decreases as the system approaches a fully periodic state. This peak consistently occurs in the SNA regime, which occurs prior to the onset of order, identifying that the state of SNA has the maximal complexity (refer to Fig. 1 a,c,e,i,j).

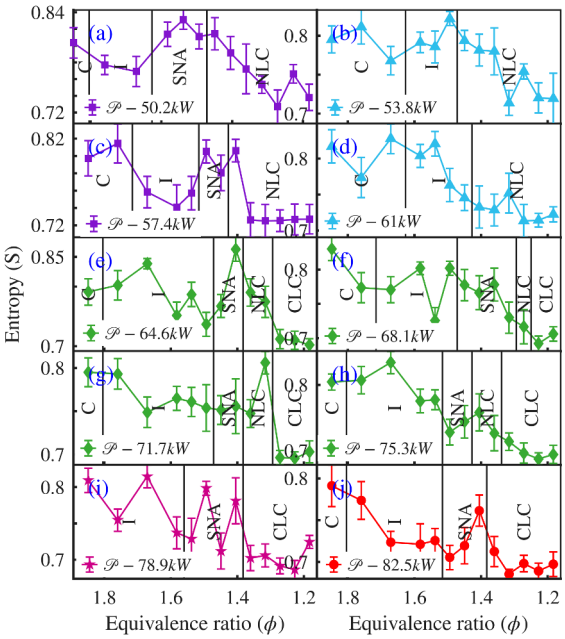

Figure 1: Evolution of entropy (as a function of equivalence ratio (ϕ)) during the transition of acoustic pressure fluctuations from chaos to periodic oscillations at different values of the secondary parameter (thermal power input ($\mathcal{P}$)). Transitions following similar dynamical routes are consistently color-coded and marked. The observed dynamical states include chaos (C), intermittency (I), strange nonchaotic attractor (SNA), noisy limit cycle (NLC), and clean limit cycle (CLC).

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Emergence of Extreme Events in an autonomous 3D Chen Chaotic System: Numerical Studies and Experimental Verification

Umar Malik J.[1], Ishaq Ahamed A. [1], Sabarathenam [2]. Thamilmaran K. [3]

[1]Department of Physics, Jamal Mohamed College (Autonomous),
Affiliated to Bharathidasan University, Tiruchirappalli, India
[2] Laboratory of Complex Systems Modelling and Control, Faculty of Computer Science, National Research University, High School of Economics, Moscow, Russia
[3]Centre for Nonlinear Systems, Chennai Institute of Technology, Chennai, India

In this study we report a simple 3D Chen-like system [1] wherein the impact of inertial torque and chaotic energy recycling lead to chaotic nonlinear processes and extreme events for proper choice of system parameters. Extreme events refer to sudden abnormal deviations in certain dynamical variables from their normal behavior causing the time scales of the system state variables to exceed significantly their long-term average. These sudden abnormalities arise purely due to deterministic causes rather than the environmental factors and often lead to profound consequences in both natural and man-made systems.

In the numerical study [2] of the 3D Chen system, we set out to identify and characterize the extreme events that occur. Conseuently, we have identified the equilibria of the system and classified them, constructed two parameter phase diagrams and one parameter bifurcation diagrams, return maps, probability distribution functions. We have also carried out real time hardware experiments on the system. To the best of our knowledge, real time experiments on this system have not been reported previously. The experimental observations are closely in agreement with those of the numerical simulations.

Keywords: Chen system, equilibrium points, return maps, two parameter phase diagrams, probability distribution functions.

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Projective and function projective synchronization of neural networks and applications to secure communications

Vaibhav Agrawal[1], Ahindra sarkar[1], Vineet Kumar Singh[1], Subir Das[1]

[1]Indian Institute of Technology(Banaras Hindu University), Varanasi, UP, India

This study addresses projective synchronization (PS) and function projective synchronization (FPS) in quaternion-valued inertial neural networks (QVINNs) with generalized delays. A generalized delay-based lemma is proposed to establish synchronization criteria. Effective controllers are designed to guarantee PS and FPS between the drive and response systems. Using one-norm technique, sufficient conditions are derived for the reduced system. Two main theorems, Theorem 1 and Theorem 2, are presented. Theorem 1 has employed a complex Lyapunov function in the non-reduced case, while the Theorem 2 has adopted a simpler one-norm-based Lyapunov approach. The proposed framework reduces computational complexity and simplifies the proof process. Additionally, an audio encryption scheme based on random permutation matrix and synchronization is developed, and the results are validated through numerical simulations, confirming the effectiveness of the proposed results.

Noise resilience of spin quantum battery in the presence of DM interactions

B. Vigneshwar[1], R. Sankaranarayanan[1]

[1]Department of Physics, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India.

Ergotropy is defined as the maximum extractable work from a quantum system without changing its entropy [1]. In implementation, it is obtained by minimizing the energy of the state ρ with respect to the Hamiltonian H, under entropy conserving unitary processes $\{V\}$.

$$\xi(\rho, H) = Tr(\rho H) - \min_{V} Tr(V\rho V^{\dagger} H). \qquad (1)$$

We investigate the role of environmental noise in limiting the performance of quantum batteries, where the extractable work is characterized by ergotropy. In particular, we focus on the storage phase of quantum batteries and examine how noise exposure affects stored ergotropy. For a single-qubit system, we analyze the effects of repeated exposure to common noise channels—namely amplitude damping, bit-flip, and phase-flip processes. Our results show that both amplitude damping and bit-flip noise lead to a progressive degradation of ergotropy, whereas phase-flip noise allows for partial retention of extractable work under repeated application.

We then extend our study to a two-qubit Heisenberg XYZ spin model incorporating Dzyaloshinsky-Moriya interaction (DMI). In this setting, we demonstrate that increasing the strength of DMI enhances the system's energy gap and promotes robust chiral correlations. As a consequence, the system exhibits improved resilience against noise, with ergotropy persisting in regimes dominated by strong DMI, particularly for coherent initial states. These findings suggest that chiral spin interactions can act as a microscopic resource for stabilizing energy storage and improving the robustness of quantum batteries under realistic noisy conditions [2].

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Molecular Dynamics study of elastic behaviour of Fibrin using unfolding-incorporated Coarse-Grained model

Vivek Sharma[1], Poulomi Sadhukhan[1]

[1]Department of Physics, Bennettt University, Greater Noida, India

We use molecular dynamics to explain the mechanical behaviour of fibrinogen which is a monomeric unit of fibrin and the main constituent of blood clot. Fibrinogen forms fibrin fiber and network through the half-staggered packing via knob-hole interaction and the αC crosslinkers[1]. Due to its complex structure, the elastic behavior shows a unique nature of very high stretchability and multiple regimes in stress-strain behaviour, which is not yet fully understood. We developed an unfolding-incorporated coarse-grained polymer (UCGP) model for fibrinogen[2] that takes protein unfolding into account to quantify the force-extension behaviour of the fibrinogen molecule. Our model finds good agreement with all-atom simulation and experimental observations[3], and provides a way to explain the mechanical characteristics of fibrinogen using molecular dynamics. We further extend our model to fibrin fiber and fibrin network to study the the mechanical behavior of fibrin fiber and fibrin network. We anticipate that our model is the simplest model which will be able to account for the nonlinear elastic behaviour of crosslinked fibrin gel, including the multiple regimes in stress-strain behaviour. This model can also be used to model the elastic properties of systems that have sacrificial bonds.

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Symmetry breaking in a meta-population model with fitness-dependent dispersal

Vikram V[1], Chandrasekar V. K[1], Gopal R[1]

[1]Department of Physics, Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613 401, India

We investigate the emergence of symmetry-breaking dynamics and the associated bifurcation structure in an identically coupled Rosenzweig-MacArthur (RM) model with fitness-dependent predator dispersal between patches. Our study reveals the occurrence of a symmetry-breaking (SB) state, characterized by unequal oscillation amplitudes across patches, indicating a form of desynchronization that promotes species persistence.

As the predator dispersal rate is varied, the system exhibits a sequence of dynamical transitions within the SB regime, alternating between chaotic and periodic symmetry-breaking states (CSB and PSB). Notably, periodic windows are found to emerge within chaotic regimes across the dispersal parameter space. The coexistence of chaotic and periodic behaviors is confirmed through Lyapunov exponent analysis.

In addition to SB dynamics, the system also displays anti-phase synchronized (APS) and in-phase synchronized (IPS) states. To further characterize the system behavior, we examine the basins of attraction in multi-stable regions, highlighting the sensitivity to initial conditions. Finally, the stability of APS, PSB, and IPS states is established using Floquet analysis.

As, synchronization is detrimental to species survival, often leading to simultaneous population crashes, exploring mechanisms that promote desynchronization becomes crucial. Our study reports the emergence of several desynchronized states, including anti-phase synchronization and symmetry breaking. Each of these dynamical regimes exhibits a degree of spatial asynchrony, which enhances the overall persistence and resilience of the species.Our results may offer valuable insights for theoretical ecologists investigating complex interactions in such systems. A natural extension of this work would be to explore fitness-dependent dispersal involving both prey and predator species, and to examine the effects of more complex network topologies beyond simple patch structures.

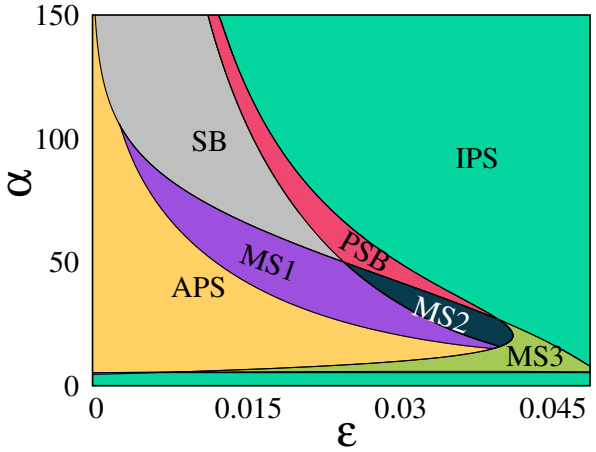

Figure 1: Span of various dynamical states observed in a prey-predator model with fitness dependent dispersal. Here, MS1, MS2 and MS3 denote multi-stable regions.

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A minimal active oscillator model for cochlear mechanics

Vidyunmathi N A[1], Toby Joseph[1]

[1]Physics Department, BITS-Pilani, K K Birla Goa Campus, India

Hopf oscillators are widely used as candidate models for cochlear dynamics. The key features of the active process in the inner ear—compressive nonlinearity, amplification, frequency selectivity, and otoacoustic emissions—are also exhibited by oscillators near a Hopf bifurcation[1]. Most existing models are based on the normal form, which provides a phenomenological description of the dynamics near criticality [2]. It is therefore worthwhile to consider oscillator models motivated by possible physical mechanisms that give rise to these features of the active process.

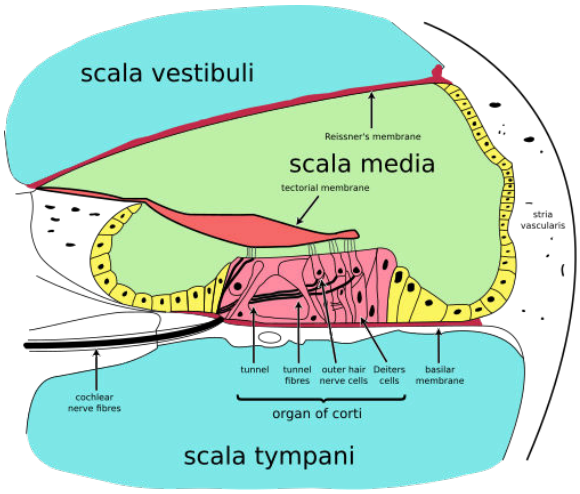

Figure 1: Cross-sectional view of Cochlea. Image taken from Wikipedia [3].

In this work, we investigate a minimal model consisting of a single underdamped oscillator with displacement-dependent nonlinear behaviour, which serves as a candidate model for a local segment of the basilar membrane–organ of Corti system. The model enables a transition between passive dissipation and active amplification.

We analyze the dynamics of the system near a supercritical Hopf bifurcation under pure tone forcing. At low forcing amplitudes, corresponding to small displacements, the behavior of the model is well described by the normal form of the Hopf bifurcation. As the forcing amplitude increases, the model exhibits qualitative features beyond those captured by the normal form.

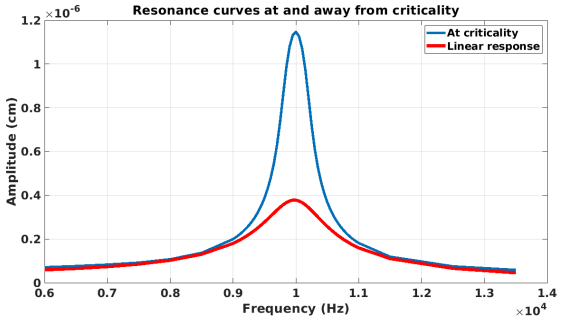

Figure 2: Resonance curve of the oscillator model. The response at criticality exhibits a sharper and enhanced peak compared to the linear response.

Under external forcing, the oscillator shows nonlinear amplification near its characteristic frequency, while the response becomes effectively linear away from resonance. Notably, the model retains a pronounced resonance peak at higher forcing amplitudes. Above the bifurcation, the system supports stable limit-cycle oscillations consistent with Hopf normal form predictions.

These results demonstrate that while the normal form captures the leading-order behavior near criticality, minimal physically motivated models can capture additional features of the response at larger amplitudes. This provides a useful framework for understanding active nonlinear processes in cochlear mechanics.

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Chimera-Like States in a Nonlocal Logistic Map Lattice

Vismaya Prasad K.[1,2], **V. Resmi**[1], **G. Ambika**[3]

[1]Pookkoya Thangal Memorial Government College, Perinthalmanna, INDIA – 679 322
[2]NSS Training College, Ottappalam, INDIA – 670 101
[3]Indian Institute of Science Education and Research, Thiruvananthapuram, INDIA – 695 551

We study the dynamics of a coupled map lattice of logistic maps in the chaotic regime with nonlocal coupling. We demonstrate the emergence of chimera-like states for coupling strengths below the global synchronization threshold. For small coupling strengths, the lattice splits into clusters of near-synchronized sites separated by unsynchronized sites. As the coupling strength increases while remaining below the synchronization threshold, the lattice exhibits an intermittent chimera state characterized by temporal switching between fully synchronized and partially desynchronized states.

2

Modulational instability in a Variable-Coefficient Nonlinear Schrodinger Equation as an envelope model for Action Potential Solitons

Yaseen M. Lone, Parasuraman E.

Department of Physics, School of Advanced Sciences, Vellore Institute of Technology, Vandalur-Kelambakkam Road, Chennai, 600127, Tamil Nadu, India

Modulational instability (MI) is a fundamental mechanism in nonlinear wave dynamics, where a continuous wave (CW) of constant amplitude becomes unstable under the effect of long wavelength perturbations. As MI progresses, small perturbations evolve into well-defined wave structures such as soliton trains, breathers and rogue waves. In some systems, such as nonlinear optics it manifests itself as an exponential growth of two spectrally symmetric sidebands on top of a plane wave initial condition. MI is known to exist in different branches of physics such as magnetic materials, optical fibres, Bose-Einstein condensates and solid-state physics. Beyond these mentioned areas, nonlinear wave phenomena are of particular interest in biological systems, where signal propagation often displays characteristics similar to localized wave structures. Such coherent excitations have been extensively studied as robust modes of information transmission and energy transport.

Models for neuronal signalling based on soliton theory have emerged as a compelling alternative to purely electrical descriptions given by Hodgkin-Huxley (HH) model. Although HH model has been remarkably successful, its sole dependance on electrical properties of neuronal membrane has motivated the exploration of alternative descriptions that capture some essential features of nerve pulse propagation related to thermodynamic and mechanical properties of biomembranes and nerves. For this purpose, the thermodynamic soliton model provides a complementary description by proposing that nerve pulses can be interpreted as nonlinear density waves in lipid membranes. The thermodynamic soliton model, in particular interprets nerve pulses as nonlinear density waves in biomembranes and nerves, arising from thermodynamic and mechanical properties such as elasticity and compressibility near phase transitions. Nonlinear envelope models have been employed to describe the evolution of such density waves. Therefore, in this context, we consider the variable-coefficient nonlinear Schrodinger equation of the form

$$i\frac{\partial\Phi}{\partial\tau_2}+\alpha\frac{\partial^2\Phi}{\partial\xi_1^2}+\beta_1 e^{-2\lambda\tau_2}|\Phi|^2\Phi+\beta_2 e^{-4\lambda\tau_2}|\Phi|^4\Phi=0, \tag{1}$$

The above equation incorporates both cubic and quintic nonlinearities with exponentially varying coefficients. Such an equation naturally emerges as an effective envelope model via multiple-scale expansion analysis in weakly nonlinear and dissipative systems. The primary focus is on the MI of a continuous wave background in this non-autonomous system. We therefore investigate the MI of a continuous wave background in this non-autonomous system and the combined effects of dispersion, cubic nonlinearity and higher-order quintic contributions are examined. It is shown that the the system dependent parameters significantly modify the standard instability, leading to the growth of sidebands and system dependent MI growth. Therefore, the study highlights the role of MI in exploring the system dependent stability properties of nerve signalling that manifest as localized excitations in complex biological media

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Gapless points in dispersion relation in Topological Phase Transitions

Zakia Huma[1], **Siddhartha Lal**[1]

[1]IISER Kolkata, India

A phase transition is a process where a system changes its phase as we change some external parameters[cite: 256]. Some of these phase transitions could be explained via the Landau's framework of expanding the free energy in powers of the order parameter[cite: 257]. In the continuous phase transitions, the order parameter which is local, distinguishes between the symmetry broken and unbroken phases[cite: 258]. For example, magnetization is zero in para phase and non-zero in ferro phase[cite: 259]. Landau theory provides important insights into the critical phenomenon of a vast array of systems such as Bose-Einstein condensates, superfluids, superconductors, liquid crystals, ferromagnets, antiferromagnets, etc[cite: 260]. Ginzburg-Landau theory which incorporates spatial variations in the order parameter, can explain key phenomenon in superconductivity such as dissipation current, Meissner effect, and magnetic vortices[cite: 260].

In topological phase transitions, the order parameter is not local but some global topological invariants like Berry phase, winding index, Chern number, etc., that changes from trivial to some non-trivial quantized value[cite: 261]. In the Integer quantum Hall effect, the state responsible for the quantum Hall effect does not break any symmetries, but it defines a topological phase in the sense that certain fundamental properties (such as the quantized value of the Hall conductance, and the number of gapless boundary modes) are insensitive to smooth changes in materials parameters and can not change unless the system passes through a quantum phase transition[cite: 272].

In spin polarized 1D superconductor (Kitaev chain), non-trivial phase can hold robust boundary states that can be used as qubits which has application in quantum computation[cite: 273]. The dispersion for this system is:

$$E(k) = \pm\sqrt{(-\mu - 2t\cos k)^2 + (\Delta \sin k)^2} \quad (1)$$

where μ is the chemical potential, t is the hopping parameter and Δ is superconducting pair term[cite: 275, 276, 278]. Here, the non-trivial phase corresponds to $|\mu| < 2t$ which has winding index $(w) = 1$ and the trivial phase corresponds to $|\mu| > 2t$ which has $w = 0$[cite: 262].

Topological landau theory: If the order parameter comprises multiple components that transform under the same irreducible representation then under the close loop variation of the parameters, the order parameter can acquire a Berry phase which signals non-trivial phase[cite: 263]. For a 3D superconductor with D_{4h} symmetry with an interaction which is the thermodynamical analog of a $(2+1)D$ Dirac point results in a non trivial phase with a quantized Berry phase in the interaction part of the Hamiltonian[cite: 264].

Taking inspiration from topological phase transition in the kitaev chain which is tracked via gapless point in the dispersion, we find a gapless point in the dispersion for this system of 3D superconductor with D_{4h} symmetry as well[cite: 266]. Thus, we see a gapless point in the dispersion along with the gapless point in the interaction[cite: 267].

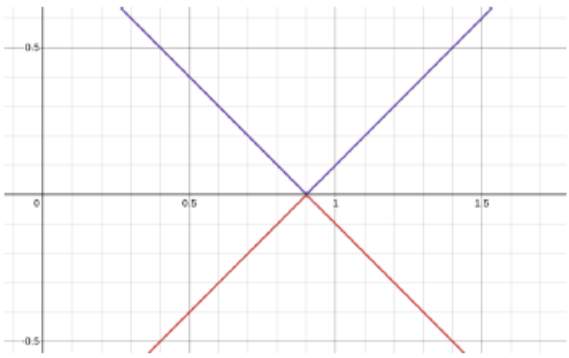

Figure 1: Gapless point in the plot of dispersion relation of the 3D superconductor with D_{4h} symmetry with $(2+1)D$ dirac like interaction.

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Mini Symposia

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Equilibrium States and Novel Bifurcation Transitions in a Periodically Driven Fluid Suspension

Anil Kumar C V

Department of Mathematics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India-695547

The orientation dynamics of a periodically driven spheroidal particle suspended in a fluid medium has been of considerable importance due to its theoretical and practical application [1, 2, 5]. Viewing the problem as a dynamical system governed by a system of ODEs enables a detailed analysis of the stability and bifurcation of long-time responses and equilibrium states in the particle transport problem, which is of interest to the nonlinear dynamics community. [3, 4]. This work proposes two novel types of bifurcation in a nonlinear system, to the best of our knowledge.

In this work, we investigate the equilibrium structure and bifurcation behavior of the nonlinear non-autonomous equations governing the orientation dynamics of periodically forced spheroids in an oscillatory shear flow given by,

$$\begin{aligned}\frac{du_1}{dt} &= (P(1-2u_1^2)+Q)u_2\cos(\omega_1 t) + Rb_1\cos(\omega_2 t)\\ \frac{du_2}{dt} &= (P(1-2u_2^2)-Q)u_1\cos(\omega_1 t) + Rb_2\cos(\omega_2 t)\\ \frac{du_3}{dt} &= -2Pu_1u_2u_3\cos(\omega_1 t) + Rb_3\cos(\omega_2 t)\end{aligned} \tag{1}$$

with,

$$\begin{aligned}b_1 &= u_3(u_3k_1 - u_1k_3) - u_2(u_1k_2 - u_2k_1)\\ b_2 &= u_1(u_1k_2 - u_2k_1) - u_3(u_2k_3 - u_3k_2)\\ b_3 &= u_2(u_2k_3 - u_3k_2) - u_1(u_3k_1 - u_1k_3)\\ P &= \frac{{r_e}^2-1}{2({r_e}^2+1)},\ Q = \frac{1}{2},\\ R &= \frac{3{r_e}^4[\beta(2{r_e}^2-1)-1]}{16\pi(r_e^2-1)(r_e^2+1)}\\ \beta &= \begin{cases}\frac{ln[r_e+(r_e^2-1)^{\frac{1}{2}}]}{r_e(r_e^2-1)^{\frac{1}{2}}}, & \text{if } r_e>1\\ \frac{cos^{-1}(r_e)}{r_e(1-r_e^2)^{\frac{1}{2}}}, & \text{if } r_e<1,\end{cases}\end{aligned} \tag{2}$$

where $\boldsymbol{u} = (u_1, u_2, u_3)$ is the unit orientation vector of the spheroid at time t, r_e is the particle aspect ratio, (k_1, k_2, k_3) is the orientation independent part of the external torque, ω_1 and ω_2 are the frequencies of the flow and externally induced torque [6]. A schematic diagram of the dilute solid-fluid suspension is shown in figure 1. As the simplest case preserving the coupling among the equations, we consider an induced external torque in the y-direction, *i.e.*, $k_1 = k_3 = 0$, and $k_2 \neq 0$. These conditions correspond to the physical scenario where the applied torque and the flow directions are perpendicular to each other. The Equilibrium state solutions of the system exist only when flow oscillations synchronize with external periodic force, given as [7],

$$\left.\begin{aligned}u_1^* &= \frac{-k_2R}{(P-Q)}\\ u_2^* &= 0\\ u_3^* &= \pm\frac{\sqrt{(P-Q)^2\alpha^2-(k_2R)^2}}{(P-Q)}\end{aligned}\right\}. \tag{3}$$

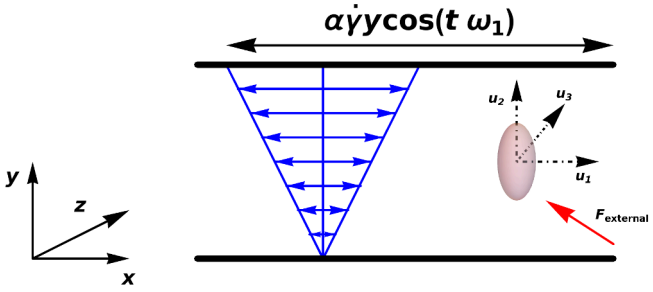


Figure 1: A schematic representation of a spheroid suspended in an oscillating shear flow under the action of an external torque.

The real-valued equilibrium states exist up to a critical torque (k_2^c) that depends parametrically on the spheroid's aspect ratio and is given as,

$$k_2^c = k_2(r_e) = \frac{16\pi(r_e^2-1)}{3{r_e}^4[\beta(2{r_e}^2-1)-1]}. \tag{4}$$

Below this threshold, the equilibria are static, neutrally stable nonlinear centers confined to a two-dimensional invariant manifold. At the critical torque k_2^c, a resonance condition—where the imposed flow oscillations synchronize with the external periodic torque—induces the coalescence of two centers into a single center. This event constitutes a novel bifurcation mechanism in non-Brownian spheroidal dynamics, characterized by the collision of two neutrally stable centers. A bifurcation diagram is shown in figure 2 for particles of certain aspect ratios upto the critical torque k_2^c. The figure 3 shows component wise evolution of equilibrium states with respect to the magnitude of the external torque k_2 is shown. Upon crossing the critical value, the orientation vector transitions from stationary equilibria to periodic orbits, yielding a resonance solution that demonstrates

the existence of physically realizable equilibrium states in a non-autonomous system.

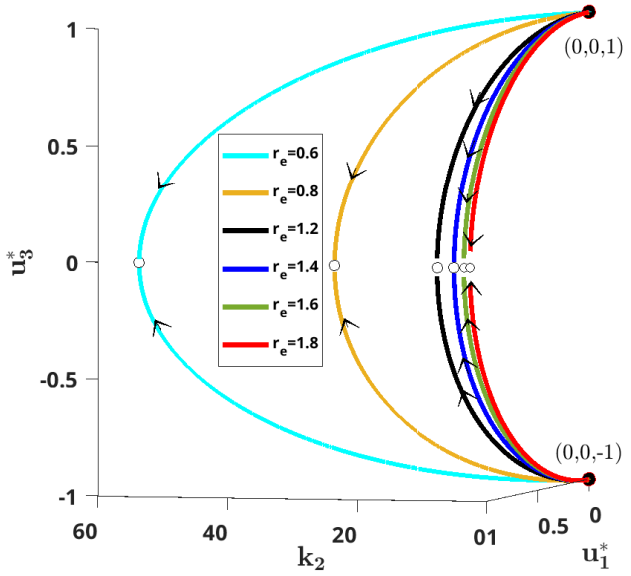
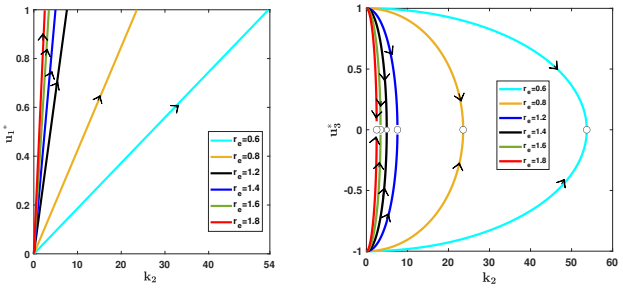


Figure 2: The static equilibrium states of spheroids suspended in a simple ($\omega_1 = 0$) shear flow under the influence of constant ($\omega_2 = 0$) external torque with $k_1 = k_3 = 0$, as k_2 varies in the regime $[0, k_2^c]$. The white bullets indicate the static fixed point at $k_2 = k_2^c$.



(a) u_1^* (b) u_3^*

Figure 3: The components of static equilibrium states, (*a*) u_1^* and (*b*) u_3^* for the cases given in Fig. 2.

In contrast, when the external torque is constant in simple shear flow, the neutrally stable centers reorganize into an unstable node at the critical torque, giving rise to a center–node bifurcation. With further increase in torque, the unstable node transforms into a complex conjugate pair, producing a ghost bifurcation and shifting toward new orientations. Ultimately, for sufficiently large torques, the spheroid aligns with the direction of the applied torque.

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Hopf bifurcation in sedimentation dynamics of a non-spherical particle

Ajeena Joseph and Anil Kumar C V

Department of Mathematics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India-695547

We report a novel type of Hopf bifurcation in the sedimentation dynamics of a sinusoidally driven non-spherical micro-particle suspended in an incompressible Newtonian fluid. The model leads to a second-order non-autonomous integro-differential equation for $0 \leq \epsilon \leq 0.35$, ϵ is the eccentricity of the near sphere. We convert this equation into an ordinary differential equation,

$$\ddot{u}(\theta) + a_1\dot{u}(\theta) + a_2 u(\theta) = f_1(\theta) + f_2(\theta) + f_3(\theta), \tag{1}$$

by introducing Reimann-Liouville integral, where $u(0) = -1$, $\dot{u}(0) = \frac{1}{2+k\,k_2}$,
$a_1 = \frac{4k_1-(9k_3^2-2k_1k_2)k}{(2+k\,k_2)^2}$, $a_2 = \frac{k_1^2}{(2+k\,k_2)^2}$,
$k_1 = \frac{\left(1+\frac{4}{5}\epsilon+\frac{2}{175}\epsilon^2\right)}{(1+\epsilon)^2}$,
$k_2 = \frac{\left(1+\frac{16}{5}\epsilon+\frac{604}{175}\epsilon^2\right)}{(1+\epsilon)^2}$, $k_3 = \frac{\left(1+\frac{8}{5}\epsilon+\frac{116}{175}\epsilon^2\right)}{(1+\epsilon)^2}$,
$f_1(\theta) = \frac{k_1(1-k_1)}{(2+kk_2)^2} - \frac{3k_3\sqrt{k}}{\sqrt{\pi}(2+kk_2)^2\sqrt{\theta}}$,
$f_2(\theta) = \cos(\omega_s\theta)\left[\frac{3\tilde{A}\sqrt{k\omega_s}k_3}{\sqrt{2}(2+kk_2)^2} + \frac{\tilde{A}\omega_s}{(2+kk_2)}\right]$
$+ \sin(\omega_s\theta)\left[\frac{3\tilde{A}\sqrt{k\omega_s}k_3}{\sqrt{2}(2+kk_2)^2} + \frac{\tilde{A}k_1}{(2+kk_2)^2}\right]$,
$f_3(\theta) = \frac{3\tilde{A}\sqrt{k}\omega_s}{2\sqrt{\pi}(2+kk_2)^2\theta^{3/2}}$, $\tilde{A}$ is the amplitude, $\tilde{\omega} = \frac{\omega_s}{t_s}$ frequency of the externally applied force, t_s is the characteristic time scale and k is the density ratio of fluid to particle. Equivalently, Eq. 1 can be expressed as a system of equations $\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \theta)$, where $\mathbf{x} = (x_1, x_2, x_3)$ with $x_1 = u$ representing velocity, $x_2 = \dot{x_1}$ denoting the acceleration of the particle, and $x_3 = \theta$ is the characteristic time.

Trivially, there exist no classical equilibrium points to Eq. 1, as the system is non-autonomous, whereas a periodic or quasi-period solution exists. Poincaré sections for non-integer frequencies of the external force reveal existence of quasi periodic motion. For a given ϵ, Eq. 1 is numerically solved by varying the parameter k. As k varies from 0, the motion shows a periodic behavior in (x_1, x_2) phase plane, and as k reaches $k_c(\epsilon)$, a critical value depending on ϵ, the orbit looses its stability and becomes neutrally stable. The behavior of this orbit changes to an unstable periodic orbit for $k > k_c(\epsilon)$, and thus undergoes a new type of Hopf bifurcation. In other words, the stable spiral (helical structure) behavior in (x_1, x_2, x_3) phase plane (for heavy particle) changes to an unstable spiral (for lighter particle) through a neutrally stable periodic orbit in long time limit. This observation is also substantiated by the analytical solution in the limiting case.

It is well known that, sedimentation dynamics under gravity results in attaining terminal velocity of the particle with no oscillation. In this study we find that, the applied external forces causes the particle to settle with the terminal velocity with oscillations, giving birth to novel Hopf bifurcation. That is, the initial transient behavior damped after some time, and the steady state oscillations are dominated by the particular solutions corresponding to the harmonic excitation in the limiting case.

In contrast to the sedimentation dynamics of spherical particle for which the terminal velocity approaches 0 in the steady state, the non-spherical particle attains a non-zero terminal velocity. The magnitude of terminal velocity and the time taken to reach the steady state depend on particle geometry. Interestingly, the time for attaining steady state and the magnitude of terminal velocity is higher for oblate spheroid compared to sphere and prolate spheroid. This difference could be due to the large surface area in contact with the fluid.

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Nonlinear Normal Modes of a Thin, Highly Flexible Cantilever Beam Using an Energy Balance Approach

Renjith A R[1], I. R. Praveen Krishna[1]

[1]Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Trivandrum, Kerala, India

An energy balance-based approach is used to study the steady-state characteristics of autonomous nonlinear systems. The total energy, a scalar quantity, is used to characterize the system. The Hamiltonian of the system is considered an additional constraint. Semi-analytical techniques are used to evaluate steady-state solutions directly. The time variational energy method is used in this approach as it can handle nonlinearity in the time domain without any frequency–time domain transformation. The time variational energy method is validated against numerical integration. The nonlinear normal mode (NNM) motions are realized using the input energy from the frequency–energy plot corresponding to the NNM for the time variational energy method. The method is applied to a discrete nonlinear system and a cantilever system with tip nonlinearity, and the NNM motions are realized. The nonlinear free vibration characteristics of a thin, long, and highly flexible cantilever beam of aspect ratio 644:1 (with length 0.95 m) using the evaluation of nonlinear normal modes. The nonlinear normal modes of the beam are evaluated experimentally from the free decay response after the nonlinear normal mode appropriation using the phase resonance approach, satisfying the appropriation criteria. The beam is modelled for computations using gradient-deficient beam elements of Absolute Nodal Coordinate Formulation, with bending deformation defined using curvature terms to incorporate the rigid body motions. The degrees of freedom of every element have nonlinear terms associated with them due to the highly coupled system matrices. Therefore, the Time Variational Method is used to extract nonlinear normal modes, thereby easing the requirement for domain transformation for handling nonlinearity, compared with other solution techniques. The comparison of the results shows that they agree. The first nonlinear normal mode appropriated response shows the presence of super-harmonics both experimentally and computationally. The experiments show no significant softening or hardening behaviour of the beam near the first nonlinear normal mode, while the computations show a slight hardening behaviour. The appropriate response shows the presence of subharmonics and superharmonics for the second nonlinear normal mode. Both experiments and computations could predict the softening behaviour associated with the second nonlinear normal mode. At higher energy levels, there is a transition in the mode shapes for the second nonlinear normal mode, and even a chaotic behaviour was observed. The time variational energy method could predict the nonlinear normal mode motions and showed good agreement with the NNM motions obtained using the time variational method and from experiments. The internal resonances were also predicted accurately using this method.

From Attractors to Networks: Forecasting Chaotic Dynamics through Time-Series-Induced Networks

K. Satheesh Kumar

Kerala University of Digital Sciences, Innovation and Technology (Digital University Kerala), Technopark Phase IV, Kerala 695317, India

Forecasting chaotic and hyperchaotic time series remains difficult because local divergence of nearby trajectories rapidly degrades predictive accuracy, especially when conventional methods rely either on local linearisation or on black-box learning with limited dynamical interpretability. In this talk, I present a time-series-induced network framework in which a scalar time series is first reconstructed in delay space and then converted into a symbolic representation that yields a directed weighted network acting as a coarse-grained image of the underlying attractor. In the earlier formulation, developed for hyperchaotic systems, repeating local orbit patterns are grouped into network neighborhoods, and multistep forecasts are obtained by following the dominant transitions in this symbolic state space. This leads to improved prediction horizon and accuracy relative to linear first-order and earlier network-based approaches, while also offering a discrete model flow on the attractor itself [1].

Its applicability to real-world nonlinear data is demonstrated through an adapted symbolic dynamic network model for wind speed forecasting. Two modifications are central here: data-adaptive symbolic discretisation using k-centroid clustering, and a fallback pattern-matching rule based on Levenshtein similarity instead of Euclidean comparison in symbolic space. These changes improve computational efficiency, better respect non-uniform empirical distributions, and enhance forecast quality. The resulting model gives accurate short-term multistep forecasts, compares favorably with conventional nonlinear and machine-learning baselines, and also shows notable spatial generalisability across nearby locations using a network built from a single reference site [2].

The broader point of the talk is that time-series-induced networks can serve not only as descriptive tools for nonlinear dynamics, but also as more interpretable predictive models that bridge attractor geometry, symbolic dynamics, and real-world forecasting. This makes them a useful framework for studying complex dynamical systems at the interface of nonlinear science, network theory, and data-driven modelling.

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On the space of topologically sensitive maps

Vinod Kumar P B

Muthoot Institute of Technology and Science (Autonomous), Kochi, Kerala, India.

This talk presents a comprehensive synthesis of the global topological structure and rigid boundary behaviours of topologically sensitive dynamical systems. Building upon the cover-theoretic formulation of sensitive dependence on initial conditions, we investigate the space of topologically sensitive self-maps, $S_{\text{top}}(X)$, under the compact-open topology. We establish that for compact metrizable spaces, $S_{\text{top}}(X)$ forms an $F_{\sigma\delta}$ set and is residual in the sense of Baire when a dense set of weakly positively expansive maps exists. Furthermore, we resolve the boundary of Devaney's chaos conditions in non-metrizable spaces by proving that transitivity and dense periodicity force topological sensitivity strictly in infinite Urysohn spaces, while failing entirely in weaker T_1 topologies (e.g., the cofinite topology). We also demonstrate that weak mixing universally forces topological sensitivity given disjoint closed neighbourhood separation. Finally, we establish advanced structural theorems confirming the propagation of topological sensitivity in cartesian products, its strict and absolute incompatibility with a newly formalized notion of topological equicontinuity, and the existence of rigid topological barriers—specifically proving that the Stone–Cech remainders of real compact spaces (acting as almost P-spaces) categorically cannot support topologically sensitive maps.

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