Poster Session B

Saturday Jan. 4, 7:30PM-9:30PM

B1 - Computational Topology Techniques for Detecting Exoplanet Signatures in Circumstellar Disks

Elizabeth Bradley, University of Colorado at Boulder; Morgan Byers, University of Colorado at Boulder; Jay Chittidi, Johns Hopkins University; Meredith MacGregor, Johns Hopkins University; James D. Meiss, University of Colorado at Boulder

The Atacama Large Millimeter/submillimeter Array (ALMA) is the largest radio interferometer in existence. Capable of extremely high-resolution observations, ALMA has revolutionized our understanding of how planets form. In nearly all of the circumstellar disks it has observed, ALMA has revealed previously hidden signatures of the dynamics of planet formation: gaps, rings, spirals, etc. Since ALMA is an interferometer, its observations contain structured patterns that can obscure real structure in the images. The current standard practice for removing these artifacts is to use the CLEAN algorithm, the performance of which depends critically on user input. Even after these artifacts are removed, it can be difficult to identify salient structures in the interior rings of the resulting images because light from the bright central star washes out the faint structure of the surrounding disk. Building on classic techniques from mathematical morphology—opening/closing and Canny edge detection—we leverage the rich, multi-resolution signature produced by topological data analysis to denoise ALMA images automatically and identify the outlines of the structures that they contain.

B2 - Associative memory and basin structure in multi-state reservoir computing

Ling-Wei Kong, Cornell University; Gene A Brewer, Arizona State University; Ying-Cheng Lai, Arizona State University

Traditional neural network models of associative memories, such as the prestigious Hopfield network, were primarily used to store and retrieve static patterns. We extend this paradigm by studying the multi-state reservoir computing framework capable of storing and retrieving complex dynamical attractors, under two common recall scenarios in neuropsychology: location-addressable and content-addressable. For both scenarios, we demonstrate that a single reservoir computer (RC) can memorize a vast number of periodic and chaotic attractors, and we uncover various scaling laws governing RC capacity. We articulate control strategies for successful switching among the attractors, and unveil the mechanisms behind failed switching. Our work provides new insights into associative memory in neural networks. Additionally, we find surprisingly complex basin structures in these multi-state RCs, with novel features not observed before. These structures also exhibit characteristics similar to those in other highly multi-state systems, suggesting the generality of these features across diverse systems. Furthermore, we propose that reservoir computing, as one of the most tunable and flexible nonlinear dynamical systems, can serve as a powerful tool to explore a wide range of problems in nonlinear dynamics.

B3 - Revisiting Winfree's Firefly Machine: Experiments with Synchronous Arrays of Photuris frontalis Fireflies

Owen Martin, University of Colorado at Boulder; Nolan Bonnie (co-first author), University of Colorado at Boulder; Nicholas Barendregt, University of Colorado at Boulder; Orit Peleg, University of Colorado at Boulder and Santa Fe Institute.

In 1964 Art Winfree built a Firefly Machine, a 'polytalanton' wherein seventy-one oscillating neon lamps were coupled electrically to each other, in an effort to observe fleeting and stable instances of syntalansis, synchronization, or other effects. Sixty years later we resurrect this idea with an actual population of Photuris frontalis (snappy sync) fireflies from Congaree National Park in South Carolina. In our experiments, each of eighty-one individual fireflies is sequestered within a clear sided plastic box, carefully placed at a vertex within a 9x9 lattice on the floor of a dark tent, and observed by video recording over the course of two hours of interactions with its peers. The result is a tantalizing dataset where each individual firefly's contributions to the collective rhythm can be easily observed. In our preliminary studies we find role division in the form of leaders and followers of the emergent synchronous beat, connected components of flashing cliques, and flash propagation that can be directly traced between individuals. We additionally simulate the dynamics of a similar lattice formed by a network of integrate-and-fire oscillators to further understand the excitable dynamics that appear within the system. These experiments could provide new insights into the synchronization mechanisms within Photuris frontalis swarms, and potentially other synchronous systems like neuronal networks.

B4 - Twisted states on fractals

Matthew Mizuhara, The College of New Jersey; Georgi Medvedev, Drexel University

In the study of coupled oscillator systems, a fundamental question exists to understand the interplay between the network structure and the resultant equilibria. Twisted states are equilibria whose phases wrap around the unit circle, resulting in a non-zero winding number. They have been studied in many settings including on ring networks, lattices, and random graphs. In this work we show how twisted states can be constructed on fractals. In particular, the complex topological structure of fractals allows for a richer class of states requiring several winding numbers. Borrowing tools from fractal analysis and topology, we present a method to construct and classify twisted states on the Sierpinski Gasket and other fractals.

B5 - An Algorithmic Approach for Fostering Novel Collaboration at Conferences

Sodiq Mojeed, Santa Fe Institute; Emma Zajdela, Princeton University

Several studies have investigated the effects of team diversity on creativity in various walks of life, including science. However, existing awareness and the homophily effects among scientists often influence their choice of collaborators. Research has shown that prescribed interaction can lead to new collaborations. Therefore, this research aims to design conference interactions that mitigate these effects on team formation. To achieve this, we developed a sorting algorithm to initiate connections among the participants who never collaborated before a conference. The algorithm assigned the participants to several group meetings and maximized each group's diversity based on its members' gender, academic disciplines, and countries of residence. It also minimized repeated meetings among all possible pairs during multiple iterations of such conversations. We show that the groups generated using the algorithm are more diverse than those generated randomly. Hence, the sorting algorithm can catalyze novel interdisciplinary collaborations and, at the same time, combat homophilic effects at scientific conferences. We will describe extensions of this work to design a novel online platform that aims to support idea generation, scientific collaboration, and innovation.

B6 - Exploring Chaotic Motion with Short-Time Expansion Rates

Matthew Morena, Christopher Newport University

I present a new method for identifying the regions on a chaotic attractor that are locally more stable and hence potentially more predictable than other regions. To do this, I construct in each neighborhood of a chaotic attractor an independent coordinate system in which one axis is carefully aligned with the local flow direction and the remaining axes are aligned with the other dynamical directions. This creates a moving reference frame that evolves along a given trajectory, but is independent in the sense that its axes are determined by the attractor's local dynamical geometry and not by parametric properties of the trajectory itself. The novelty of this technique lies in its ability to consider the local dynamics of chaotic systems, while being robust to both noise and to any nonlinearities in the governing equations. I demonstrate this method with several classic chaotic, hyperchaotic, and conservative dynamical systems.

B7 - Prediction of excitable wave dynamics using machine learning

Mahesh Kumar Mulimani, University of California San Diego

Excitable systems can exhibit a variety of dynamics with different complexity, ranging from a single, stable spiral to spiral defect chaos (SDC), during which spiral waves are continuously formed and destroyed. The corresponding reaction- diffusion models, including ones for cardiac tissue, can involve a large number of variables and can be time-consuming to simulate. Here we trained a deep-learning (DL) model using snapshots from a single variable, obtained by simulating a single quasi-periodic spiral wave and SDC using a generic cardiac model. Using the trained DL model, we predicted the dynamics in both cases, using timesteps that are much larger than required for the simulations of the underlying equations. We show that the DL model is able to predict the trajectory of a quasi-periodic spiral wave and that the SDC activation patterns can be predicted for approximately one Lyapunov time. Furthermore, we show that the DL model accurately captures the statistics of termination events in SDC, including the mean termination time. Finally, we show that a DL model trained using a specific domain size is able to replicate termination statistics on larger domains, resulting in significant computational savings.

B8 - A Computational Model of Phonation-Induced Aerosolization

Corey Lynn Murphey, University of Colorado at Boulder; Allison Hilger, University of Colorado at Boulder; Elizabeth Bradley, University of Colorado at Boulder and Santa Fe Institute

In infectious speakers, speech-induced aerosolization can facilitate the transmission of airborne viruses. The formation of such aerosols is challenging to visualize experimentally due to the complex structure of the larynx, the inability to directly measure aerosol generation at the laryngeal level, and the length scale at which fluid atomization occurs. To elucidate the dynamics involved in laryngeal speech-induced aerosol formation, we have developed a two-dimensional computational multiphysics framework that models the ejection and subsequent breakup of sessile liquid on the surface of the vocal folds. A vibration-induced instability drives the emission of droplets from the fluid-lined mucosal layer of the vocal folds. We apply Tate's law to simulate the resulting ejection process as unstable fluid jets break off into droplets when the oscillatory forces in the tissue exceed the surface tension of the mucosal fluid. The movement of the tissue is modeled using a finite-element vibrational elastodynamics strategy, coupled via fluid-structure interaction methods to the airflow through the larynx. The output of this model yields a spray distribution that we compare to experimental aerosol size distributions collected during phonation tasks. From this model, we can gain insight into the role of laryngeal geometry and oscillatory dynamics in the production of aerosol, advancing our intuition about phonation-driven aerosolization and pathogen emission during speech.

B9 - Reservoir computing of chaotic dynamics from biased small training data using periodic orbits

Kengo Nakai, Okayama University; Yoshitaka Saiki, Hitotsubashi University

Reservoir computing is effective in the inference of time-series and some characteristics [1,2]. A reservoir is a recurrent neural network whose internal parameters are not adjusted to fit the data in the training process. We have succeeded in modeling a macroscopic behavior of a three-dimensional chaotic fluid flow [3]. We have also shown that manifold structures and periodic orbits can be reconstructed from a model using reservoir computing [4,5].

In this talk we show that the effect of training data for reservoir computing on the reconstruction of chaotic dynamics. Our findings indicate that a training time series comprising a few periodic orbits of low periods can sufficiently reconstruct the chaotic attractor. We also demonstrate that biased training data do not negatively impact reconstruction success. Our method's ability to reconstruct a physical measure is considerably better than the so-called cycle expansion approach, which relies on weighted averaging. For a different set of parameters, we demonstrate that fixed point attractors and chaotic transients can be reconstructed by a model trained on a few periodic orbits. In this study, using periodic orbits to generate biased small training data is significant to understanding how training data affect the construct data-driven model. This talk is mainly based on our paper [6].

[1] Z. Lu, J. Pathak, B. Hunt, M. Girvan, R. Brockett, and E. Ott, Chaos 27, 041102 (2017). [2] J. Pathak, Z. Lu, B. Hunt, M. Girvan, and E. Ott, Chaos 27, 121102 (2017). [3] K. Nakai and Y. Saiki, Phys. Rev. E 98, 023111 (2018). [4] M. Kobayashi, K. Nakai, Y. Saiki, and N. Tsutsumi, Phys. Rev. E 104, 044215 (2021). [5] M. Kobayashi, K. Nakai, and Y. Saiki, J. Phys.: Compl. 5, 025024 (2024). [6] K. Nakai and Y. Saiki, Data-driven modeling from biased small training data using periodic orbits, ArXiv:2407.06229.

B10 - Path integral approach to universal dynamics of reservoir computers

Naoto Nakano, Meiji University

We study the characterisation of the reservoir computer (RC) using the probability distribution that the coupling constants of the random network follow. Utilising the path integral method, we elucidate random network dynamics, leading to a classification of networks based on the coupling constant distribution function and the eigenvalue distribution of the matrix of the coupling constant. The findings suggest a correlation between the RC's computational capacity and network parameters across universality classes. Numerical simulations reveal superior computational performance near phase transitions. Especially we applied this method to the time series prediction of the Lorenz system. The reproducibility of the maximum Lyapunov exponent of the trained RC model was observed only near the tricritical point of the phase space. This work provides novel insights for designing a network of RC suitable for learning. This study is based on the results of the presenter's paper, "DOI: 10.1103/PhysRevE.107.034306".

B11 - A hypergraph approach relating enzyme bifunctionality and robustness in biochemical networks

Tung Nguyen, University of California Los Angeles; Badal Joshi, California State University San Marcos

A common motif in biochemical reaction networks is enzyme-catalyzed substrate modification, where one or more substrates are modified into other substrates. At a high level, each reaction can be represented in a simple manner, for example $S \to S^*$. In more detailed models, each reaction contains many reaction steps involving enzyme binding and catalysis, and one or multiple intermediate compounds. These models then can be associated with dynamical systems such as mass-action ODEs.

Typically, in the reaction network literature, people attempt to link the network structure of these detailed models to the qualitative behaviors of the associated dynamical systems such as existence, stability and robustness of the steady states. A limitation of this approach lies on the fact that the detailed steps are hard to verify experimentally. How many intermediate compounds are formed? Are the reaction steps reversible or irreversible?

Recognizing this limitation, we take a different approach and focus on the interaction networks of the substrates at high level. We represent these high level networks by hypergraphs and are able to link their properties to dynamical properties, bypassing the need to specify the detailed models.

B12 - Using reservoir computers to suppress power grid disturbances

Erin Obermayer, University of Colorado at Boulder; Juan G. Restrepo, University of Colorado at Boulder

Power grids are large and complex networks in which many generators must be synchronized to keep energy flow stable. Disturbances in these systems, such as generator failures and power surges, can lead to power outages if not immediately addressed. We propose a method to identify and suppress the effect of unanticipated disturbances to power grids based only on prior observations of the system when forced by a known training function. We present preliminary results on small power grids modeled as second-order Kuramoto models.

B13 - Spatial variation in climatic factors predicts spatial variation in mosquito abundance in the desert southwest

Kayode Oshinubi, Northern Arizona University

Mosquitoes are carriers of significant numbers of disease infections globally, such that developing models that better predict mosquito abundances is imperative. Mosquito population dynamics are particularly sensitive to local weather conditions, and previous studies have demonstrated that mosquito-borne disease outbreaks can be spatially concentrated. Using a time-series of weekly collected mosquito abundance data in Maricopa County, USA, we assess how local variation in climate can predict mosquito population dynamics. First, we built a simple mechanistic model of mosquito population dynamics that is influenced by both daily temperature and 30-day accumulated precipitation. Then, we use a time series clustering algorithm to divide Maricopa County into clusters with similar variation in precipitation, combining zip codes into clustered communities. Our goal is to evaluate the effectiveness of this cluster-based modeling for predicting mosquito abundance in Maricopa County. We then use MCMC to fit the mechanistic model using averaged climate data in each cluster. First, we show how the simple, climate-forced modeling does a good job at estimating detailed mosquito abundance trajectories throughout a ten-year period. Our clustering method was able to capture spatial variation in climate variables that was distinct from distance-based clustering. Most importantly, we discovered that this spatial variation in climate improves the fit of the model to the data, emphasizing how small-scale variation causes heterogeneities in mosquito population dynamics. Our study clearly demonstrates the importance of collecting fine-scale mosquito abundance data to improve our understanding and the predictability of mosquito population dynamics. By combining this detailed data with mechanistic modeling, we reveal the importance of temperature and precipitation for explaining complex mosquito population dynamics and the importance of spatial variation in these climate variables.

B14 - Between Behaviors: Pathways to Metastability

Denizhan Pak, Indiana University Bloomington; Randall Beer, Indiana University Bloomington

Metastable behavior is a prominent feature in many biological systems, often manifesting through transient, dynamically stable states that appear to "switch" either spontaneously or in response to external stimuli. In dynamical systems approaches, heteroclinic channels have been explored as a model for describing such metastability. However, two notable limitations of standard heteroclinic channels hinder their broad applicability: their lack of robustness to moderate noise and their reliance on stringent symmetry constraints to emerge generically. Recently, ghost channels have been proposed as an alternative that does not face these constraints, offering a more noise-resistant structure that operates independently of strict symmetry requirements. In this talk, I will delve into the distinctions between heteroclinic and ghost channels and examine their respective roles in a simplified neural-mass model. I will further illustrate how coupling this neural-mass model to a basic body model modifies the dynamics, providing insights into how these structures may support metastable behavior in biological systems and potentially shed light on neural and sensory-motor processes.

B15 - Solving pattern formation partial differential equations with finite element methods to explore their sensitivity to boundary shape and condition

Alice Quillen, University of Rochester

Systems described as active or pattern forming are often confined or influenced by solid, moving or flexible surfaces. By solving partial differential equations on triangular meshes we explore how some pattern formation models are influenced by the proximity and shape of a nearby boundary and the nature of the boundary condition.

B16 - Using complex dynamics to compute brain networks

Anca Radulescu, State University of New York at New Paltz; Sarah Muldoon, University at Buffalo; Johan Nakuci, Army Research Labs; Eva Kaslik and Alex Fikl, West University of Timisoara

The central goal of our work is to understand how global behavior in dynamic networks emerges from the interplay between the network's connectivity profile and the node-wise dynamics. We explore this direction with a novel modeling approach, in which we equip each of the network nodes with discrete quadratic dynamics in the complex plane, and we study the emerging behavior of the resulting complex quadratic network (CQN) by means of the topology of its asymptotic fractal sets (in particular, we define the extension of the Mandelbrot set for networks, which we call the equi-M set). Many of these questions are extremely difficult to address in realistic models of coupled neural oscillators, where they are deemed analytically, and often also computationally intractable. Rephrasing such questions in terms of complex map iterations presents a mathematically approachable and canonical way that allows us to place them into a unified framework and opens a wide potential for applications to network science.

We will illustrate these approaches at work in an application to brain networks. In particular, we will show how geometric landmarks of the equi-M sets computed for human brain connectomes can provide valuable means of classification and comparison of both brain connectivity and functional dynamics. As a working example, we will use a data set comprised of structural and functional connectomes for $N = 200$ subjects during multiple tasks (data provided in the public domain by the Human Connectome Project). Our results show that the equi-M set provides a useful comparison tool, which can efficiently differentiate between individuals, and is sensitive and specific to factors such as gender, connectivity type, physiological and psychological profile and behavioral task being performed.

B17 - Reservoir Computing-Based Control of Chaotic Dynamical Systems under Parameter-Driven Disturbances

Krithikesh Ravishankar, University of Colorado at Boulder; Juan G. Restrepo, University of Colorado at Boulder

This project investigates the control of an unknown chaotic dynamical system using reservoir computing, aiming to stabilize the system by mitigating parameter-driven disturbances. The model-free approach to build the controller only makes use of previous observations of the system, ensuring a robust methodology with wide ranging applications to real-world chaotic systems. The system's chaotic nature is influenced by disturbances to the system parameters themselves, effectively modifying the underlying model, causing it to dip into periodic or chaotic regimes. To address this, we apply reservoir computing alongside two control schemes: a delayed control scheme and a model predictive control (MPC) scheme and evaluate the conditions under which each scheme suppresses chaotic disturbances and maintains a periodic orbit. This work offers insights into real-time control and chaos suppression, demonstrating the potential of reservoir computing and hybrid control frameworks to manage nonlinear dynamical systems in chaotic environments.

B18 - Estimation of Nonlinear Dynamics

Nicholas Rummel, University of Colorado at Boulder; David Bortz, Vanja Dukic, Daniel Messenger, and Stephen Becker, University of Colorado at Boulder

We extend the Weak-form Estimation of Non-linear Dynamics (WENDy) algorithm to allow for systems of ordinary differential equations that are nonlinear in parameters. Furthermore, we increase the algorithm's efficiency and robustness to noise by making use of the weak form log-likelihood to derive analytic expressions for the gradient and Hessian, and incorporating them into the optimization routines suited for this non-convex optimization problem. The resulting parameter estimation algorithm has a substantially larger convergence domain than conventional nonlinear least squares based on forward solver. Moreover, the algorithm is even considerably more robust to noise than to previous weak form algorithms.

The algorithm is implemented efficiently in Julia and is able to accommodate the weak form optimization for both additive Normal and multiplicative Log-Normal noise. We present results on a suite of both linear-in-parameter and nonlinear-in-parameter systems of ordinary differential equations and compare our method to forward solver-based methods to demonstrate the practical benefits of our approach.

B19 - Community Structure and External Forcing of the Social Compass Model of Opinion Dynamics

Corbit Sampson, University of Colorado at Boulder; Juan G. Restrepo, University of Colorado at Boulder

In the social compass model, recently proposed by Ojer et al., individuals have opinions on two distinct topics which are represented in polar space with the magnitude acting as an individual's conviction and interactions modeled as sinusoidal coupling between agents, as in the Kuramoto model of phase oscillators. Here we examine the effects of partitioning the agents into two communities with distinct coupling strength for the in-group agents, individuals within the same community, and the out-group agents, those in the opposite community. We also allow forcing by external sources which broadcast a constant opinion at a constant strength to all agents, emulating the effects of media on the agents. Lastly, we make use of the strong similarity between the social compass model and the Kuramoto model to derive a reduced set of equations for the dynamics of the system by applying the Ott-Antonsen Ansatz. This provides an alternative approach to study the steady state behavior while allowing for a description of the system's dynamics.

B20 - Characterizing the Nonstationary Nature of Human Unipedal Balance

Matthew Semak, University of Northern Colorado; Ari Kaye, University of Northern Colorado

Time series typical of the anterior-postural and medial-lateral jerk during human unipedal balance are studied. Our interest is to classify certain general features found in these measurements as indicative of subjects experiencing certain medical conditions. There are suggestions that these signals are primarily deterministic (nonstationary) with a temporally evolving quasiperiodic autocorrelation structure and time-frequency spectrum. However, this structure can be rendered nearly insignificant with a simple stochastic perturbation. Moreover, much of the bulk behavior can be modeled, simply, by low-passed filtered white with a bandwidth limited to that of the original signal. Finally, with the Lempel-Ziv complexity having mild but measurable fluctuations throughout the time series, we have been led to pursue a classification scheme that attempts to track the evolution of the complexity with time. The signals have been decomposed into modes using methods such as multiresolution analysis and assessed using Lempel-Ziv complexity, with its coarse graining application, to classify bulk features and the extent to which determinism plays a role in the jerk. This allows us to be able to, then, pursue an examination of the more nuanced features contained in the signal.

B21 - Radial Basis Function Methods for Neural Field Models

Sage Shaw, University of Colorado at Boulder; Zachary Kilpatrick, University of Colorado at Boulder; Daniele Avitabile, Vrije Universiteit

Neural field models are non-linear systems of integro-differential equations intended to model large-scale neural activity. There is growing interest in identifying efficient and accurate schemes for simulating neural field models as they can capture activity dynamics that spread across wide swathes of tissues and that reflect highly complex neural architecture. Recently, a framework has been put forth for analyzing neural field solvers (Avitable 2023) that separates the error due to the numerical representation of the solution (projection) and the error due to approximating the integral operator (quadrature). In this poster, we demonstrate using Radial Basis Function (RBF) interpolation and quadrature methods to combine and simplify this error analysis and to create efficient, robust, and high-order-accurate neural field solvers.

B22 - Spectral Characterization of Eight-Phosphorus-Array Hamiltonians in Silicon

Evan Sheldon, University of Maryland, Baltimore County; Maicol Ochoa, University of Maryland College Park and National Institute of Standards and Technology

The Fermi-Hubbard model is extensively used to investigate many-body states and transformations between them. This model captures the basic physics of multi-electron systems in arrays. The full characterization of this model is a task that scales exponentially with the number of sites, quickly escaping the capacity of most classical computers. Silicon nanodevices that incorporate impurities with atomic precision are ideal materials for analog quantum simulations of the Fermi Hubbard model. In the present work, we investigate non-interacting Hamiltonians representative of arrays consisting of eight phosphorous sites, forming a ring, from a dynamical perspective. First, we consider how the probability distribution of an electron localized on a single site evolves over time. Then, we perform a Fourier analysis of these trajectories to identify the relevant frequencies, which we can use to characterize the transition probabilities between different sites. By comparing these dynamics with tight-binding calculations of the same system, we have the potential to identify tunneling energies and onsite energy corrections needed to validate silicon devices as quantum simulators. Our results suggest that this approach provides a good qualitative description of the parameter set for the non-interacting Hamiltonian, and further work is required to identify these parameters for each device uniquely.

B23 - The Effects of Temperature and Sulfuric Acid Concentration on BZ Propagating Wave Patterns

Samantha Small, Elizabethtown College; Desmond Yengi, Elizabethtown College

Waves and oscillation patterns are found at all levels of biological organization, from cellular to supracellular and even social organisms. For instance, the rhythmic beating of the heart is driven by the intricate spatiotemporal distribution of oscillatory signals in cardiac pacemaker cells, while Beta-cells in the pancreas release insulin in response to fluctuations in calcium concentrations. Similarly, amoeboid cells exhibit wave-like propagation patterns that generate movement. The Belousov-Zhabotinsky (BZ) reaction serves as a model for studying the dynamic behaviors of biological, chemical, and physical systems. This reaction involves the oxidation of an organic acid by bromate ions in acidic aqueous solution in the presence of a metal ion catalyst. When the precise conditions are met, this metal catalyst undergoes repeated oxidation and reduction cycles that can be visualized by alternating colors. Variations in the BZ reaction mixture and environmental conditions, such as temperature, affect oscillation and wave patterns. We report our investigations into the effects of temperature and sulfuric acid concentration on spontaneously propagating wave patterns in a quasi-two-dimensional BZ reaction-diffusion system conducted isothermally at temperatures between 3.0°C and 50°C. The average wave velocity, wavelength, and period measurements show a strong temperature dependence. At low acid concentrations, as temperature increases, the wave patterns transition from target to spiral and chaotic wave patterns, while in isothermal conditions, the wave patterns transition from target to spiral with increasing sulfuric acid concentration.

B24 - Scale-Locality in Compressible Turbulence: Insights into the energy cascade across scales in non-ideal shocks

Dina Soltani Tehrani, University of Rochester; Hussein Aluie, University of Rochester

Inter-scale energy transfer (or the cascade) is of relevance to both LES modeling and turbulence theory. In incompressible homogeneous isotropic turbulence, there has been compelling theoretical and empirical support that the scale-transfer of kinetic energy (KE) is local. Here, we analyze the locality of KE scale-transfer in compressible turbulence. There is a common notion that shocks and discontinuities that pervade compressible turbulence necessarily imply a non-local scale-transfer. We show this not to be the case by demonstrating rigorous proofs of scale-locality using the solution to the 1D non-ideal normal shock. Proofs of scale-locality in compressible turbulence hold in broad generality, at any Mach number, for any equation of state, and without the requirement of homogeneity or isotropy. Rather, locality rests on assumptions about the scaling of velocity, pressure, and density structure functions, which are weak and enjoy broad empirical support.

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B25 - Modelling the universal self-similar community structure of complex networks

Nidhi Sonwane, Nidhi Dilip Sonwane, Centre for Excellence for studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras; Shruti Tandon, Centre for Excellence for studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras; Tobias Braun, Institute for Earth System Science & Remote Sensing, Leipzig University, Germany and Centre for Excellence for studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras; Norbert Marwan, Potsdam Institute for Climate Impact Research (PIK) and Institute of Geoscience, University of Potsdam; Jürgen Kurths, Potsdam Institute for Climate Impact Research (PIK) and Institute of Physics, Humboldt Universität zu Berlin; R. I. Sujith, Centre for Excellence for studying Critical Transitions in Complex Systems, Indian Institute of Technology Madras.

Diverse real-world systems modelled as complex networks exhibit self-organisation in the form of hierarchical communities. We discover that multiple such systems like protein structure, protein interactions, gene interactions, neuronal network of mouse and coauthor network show a universal topological self-similarity in the form of common scaling laws. This universality implies a common underlying principle behind the formation of these networks. Here, we present a phenomenological model of a growing network that replicates the common scaling laws and explains the emergence of self-similar community structure in real-world systems.

In our model, we assign a property called status to each node that represents its inherent features, e.g., function of a protein in a protein interaction network. The probability that two nodes connect is higher if the difference between their statuses is smaller. We characterise the hierarchical community structure of networks using a binary tree where a node in the tree represents a community in the network. We then assign the Horton-Strahler order h to each node of the tree. The Horton-Strahler order was originally introduced to study bifurcations in river networks. It is associated with Horton laws that reveal the topological self-similarity in binary trees. We find that the network generated from our model has a multi-scale community structure with similar Horton laws as those observed in real-world systems. Most importantly, we show that the entropy of statuses of nodes in a community decreases linearly with the scale h. This means that the nodes try to minimise the relative differences in their statuses while forming links and an optimized global structure emerges. Moreover, the variation of mean status of nodes in a community with h looks the same as input status distribution. We thus discover the relationship between the local node properties and the emergent property of the system at multiple scales of self-organisation.

B26 - A Bounded Confidence Model of Opinion Dynamics with Contrarians

Ian Soukup, University of Colorado at Boulder; Juan G. Restrepo, University of Colorado at Boulder

Individuals' opinions are directly impacted by the opinions of those they interact with. For most, their opinions tend to gravitate towards each other as they hear new evidence or perspectives. However, some are contrarians, preferring not to agree with those around them. We study the effect of contrarian individuals in bounded confidence models of opinion dynamics. We consider the Deffuant–Weisbuch (DW) model of opinion dynamics enriched by a number of contrarians which change their opinion when a large enough number of individuals have a similar opinion to them. The presence of contrarians leads to much richer dynamics than that observed without them. In particular, we find that contrarians can drive the non-contrarian population to consensus even in situations in which polarization would be expected in their absence. We derive analytical results for the evolution of the mean opinion in the presence of one contrarian and present numerical simulations illustrating the different types of dynamics observed with multiple contrarians.

B27 - Anatomy of an odor plume: how Lagrangian flow structures drive odor dynamics and encode source information

Elle Stark, University of Colorado at Boulder; Aaron True, John Crimaldi, University of Colorado at Boulder

Animals rely on odor plume navigation for critical behaviors including finding food and mates or avoiding predators. Yet, scientific understanding of the olfaction process remains elusive, in part due to the turbulent transport that stretches, folds, and rotates odors into complex structured landscapes. In this work we investigate the relationship between flow and odor structures using a numerical simulation of a 2D chaotic flow. Lagrangian coherent structures (LCS) provide an intuitive framework for elucidating this coupling, as LCS drive the spatial organization and temporal evolution of the scalar field. Through an analysis of LCS, we identify key spatial patterns in the timing of whiffs (defined as odor pulses above a given threshold) relative to the underlying flow structure. We extend the analysis to instantaneous sensible flow cues, including strain, acceleration, and vorticity. For several flow cues, we find significant spatial structure in the timing of strong cues relative to odor whiffs, similar to the spatial information encoded in the LCS timing. Such structure could inform fundamental olfactory search tasks such as odor plume edge detection or source localization.

B28 - Undergraduates Translating Dynamics Research into Real World Applications

Randall Tagg, University of Colorado at Denver

Undergraduates (and some Masters students) have demonstrated a unique capacity to translate archetypes of nonlinear dynamics into real-world applications, some of which have led to the formation of new corporations. We will display a variety of examples including pendulum dynamics, electronic oscillators, nanoparticle electrokinetics, robotics, optical systems, and fluid dynamics. The possibility of a lab tour at CU Denver exists after the formal meeting for those who are interested in further discussion and hands-on interaction with some of our systems.

B29 - Consensus modeling for ML, human-AI teams, and multiway coordination

Dane Taylor, University of Wyoming.

Models for consensus (i.e., agreement) are widely used to study collective group decisions and engineer decentralized ML/AI algorithms. In this work, we study the role of network structure in shaping consensus dynamics. For networks with community structure, we identify a phase transition above which the communities impose a bottleneck to convergence (highlighting implications for decentralized ML). We develop a model for interconnected census systems to study human-AI teams, identifying conditions that guarantee when optimally fast decisions are cooperative (i.e., humans and AI agents mutually influencing each other, which requires the timescale for AI-AI coordination to slow to that for human-human interactions). Finally, we develop a “higher-order” generalization with consensus over simplicial complexes and study the role of network homology.

B30 - Sensitivity of epidemic forecasts with statistical condition estimation for probability generating functions

Mariah Boudreau (first author), Will Thompson (presenting), University of Vermont; Christopher M. Danforth, Jean-Gabriel Young and Laurent Hebert-Dufresne, University of Vermont

In many network-based dynamical systems, the degree distribution shapes process dynamics. For epidemic spreading, the average size of an outbreak can be calculated for random networks constrained by their degree distribution inferred from prior knowledge or estimated from contact tracing or mobility data. We use probability generating functions (PGFs) to model outbreaks of a Susceptible-Infectious-Recovered dynamical process on networks with heterogeneous degree distributions. In this analysis, the roots of the PGFs inform the probability of an outbreak as well as its expected size. Thus, when assessing the sensitivity of epidemic forecasting caused by uncertainty in the degree sequence or noise in available data, we need to evaluate the sensitivity of the polynomial's root given perturbations to its coefficients. We employ statistical condition estimation (SCE) to measure the sensitivity of the polynomial's roots and, in turn, outbreak sizes. From the SCE, we identify parameter regions, particularly those near critical transmission rates, where the model is highly sensitive to degree sequence uncertainty. Overdispersion, or variance in secondary infections, further amplifies uncertainty in near-critical regimes. Our analysis offers insight for epidemic forecasting and advances the understanding of sensitivity in dynamical systems by establishing scaling relationships at the critical transition. These findings bridge practical applications in epidemiology with theoretical developments in percolation and dynamical systems theory.

B31 - Localized Patterns on Ring Lattices

Moyi Tian, University of Colorado at Boulder; Bjorn Sandstede, Brown University; Jason Bramburger, Concordia University

The study of pattern formation in bistable systems is inspired by observations of phenomena such as ferrofluid configurations, urban crime hotspots, and vegetation patterns. While much research has focused on spatially continuous systems, little is known about the emergence of localized patterns in systems on networks. We investigate ring lattices with symmetrical coupling as an initial approach to the problem. We present analytical and numerical results that demonstrate how the network structure, determined by interaction lengths, influences the connectivity of solution branches in these systems. In particular, we find that sparse coupling and all-to-all coupling exhibit significantly different solution branches. Additionally, we provide analysis that qualitatively explains how the solution branches of localized patterns bifurcate from the homogeneous solutions.

B32 - Cluster Synchronization in Network Coupling Models Through the Eigenspectrum of the Graph Laplacian

Tobias Timofeyev, University of Vermont; Alice Patania, University of Vermont

In this work, we explore the relationship between community structures in graphs, graph Laplacian eigenvectors, and cluster synchronization in the Kuramoto model. Almost equitable partitions (AEPs) have been linked to cluster synchronization in oscillatory systems, providing a mathematical framework for understanding collective behavior. Using the spectral properties of AEPs, we can describe this synchronization behavior in terms of the graph Laplacian eigenvectors. Our results also illuminate transient hierarchical clustering as well as multiphase clustering, and the conditions under which they can occur. Through our analysis we are able to relate dynamical clustering phenomena directly to network symmetry and community detection, joining the structural and functional notions of clustering in complex networks. This bridges a crucial gap between static network topology and emergent dynamic behavior. Additionally, this description of the problem allows us to define a relaxation of an AEP we call a quasi-equitable partition (QEP). Perfect AEPs are rare in real-world networks since most have some degree of irregularity or noise. While relaxing these strict conditions, QEPs are able to maintain many of the useful properties allowing for qualitatively similar clustering behavior as with AEPs. Our findings have important implications for understanding synchronization patterns in real-world networks, from neural circuits to power grids.

B33 - Comparing the Rosenstein and Wolf algorithms in Experimental Chaos through C. elegans locomotion

Dimitrios Tzepos, Vassar College; Olivia Trader, Jenny Magnes, Vassar College;

This study quantifies the locomotion of Caenorhabditis elegans (C. elegans), a species of nematodes, through dynamic diffraction measurements. Previous work on C. elegans has indicated that their locomotion is chaotic by estimating the Largest Lyapunov Exponents (LLE) to be positive using the Rosenstein algorithm; however, this algorithm is restricted to evaluating only the LLE, ignoring the rest of the Lyapunov spectrum. The Wolf algorithm, an alternative method, can be used to estimate other Lyapunov exponents. The Lyapunov Spectrum could indicate whether or not the locomotion of the nematodes is hyperchaotic and provide estimates for the Kaplan-Yorke dimension and the Kolmogorov-Sinai Entropy of the system. We confirm that the LLEs calculated with each algorithm are consistent for the same system. The LLE using the Wolf algorithm of $1.250.05sec^{-1}$ is consistent with the LLE calculated with the Rosenstein algorithm of $1.270.04sec^{-1}$.

B34 - Information Flows in complex high-dimensional systems

Peter Jan van Leeuwen, Colorado State University

Understanding high-dimensional highly nonlinear geophysical systems remains extremely challenging. While enormous progress has been made, especially in geophysical fluid dynamics, even there large outstanding questions remain, especially in terms of predictability. A highly useful quantity to characterize would be how information flows in the system. Information content can be defined as Shannon or (one of the) Renyi entropy(ies), but efficient calculation of the high-dimensional integrals involved and useful evaluation of the resulting equation has been lacking.

Here I will demonstrate that the information flow problem can be rewritten such that all integrals are low-dimensional and that only relatively small ensemble sizes (100-1000) are needed for accurate evaluations of these integrals. The information entropy budget is calculated and information flows are determined. Physically useful quantities are derived, such as information velocity and intensity and local information generation distinguished by physical process. Interestingly, information can flow faster (or slower) than the local flow velocity, and differs for different variables in the system. It can disappear and reemerge via interesting pathways related to the underlying physical structures. Finally, we will discuss formulation of new physical processes based on information flow results.

B35 - Computational Dimension Estimates for Conformal Fractals

Erik Wendt, University of Connecticut; Vasilis Chousionis and Dmitriy Leykekhman, University of Connecticut; Mariusz Urbanski, UNT

Estimating the Hausdorff dimension of conformal fractals has been an active area of research since Jarnik's initial work in the 1920s. These estimates have applications in number theory (e.g., Zaremba's conjecture), PDEs (e.g., hyperbolic scattering theory), and hyperbolic geometry (e.g., Patterson-Sullivan theory). While many systems, such as the continued fraction IFS and the Apollonian gasket, have well-established dimension bounds, a broader theoretical and computational framework is lacking. In this presentation, I will exhibit how my thesis research bridges this gap, and showcase a fascinating application of finite element methods outside of PDEs.

B36 - Measurement of interstitial fluid flow within brain tumors from dynamic MRI using PDE regression methods, and applications thereof

Ryan Woodall, City of Hope; Michelle Wu, City of Hope; Alexander B Brummer, College of Charleston; Christine C. Brown, City of Hope; Jennifer M. Munson, Virginia Tech; Russell C. Rockne, City of Hope

High grade gliomas are aggressive brain tumors with a five-year survival of less than 6%. Thus, researchers have turned to experimental therapies such as chimeric antigen receptor (CAR) T-cell therapy, as they have shown promise [1]. The Munson laboratory has shown that both glioma cells and CAR-T cells preferentially migrate in the direction of IFF [2,3]. To measure IFF, we have developed an approach [4] using dynamic contrast enhanced (DCE) MRI. First, we construct a library of PDE terms using the known terms of an advection-diffusion-reaction equation:

$$\partial_t c = \nabla\cdot(D\nabla\cdot c) - \nabla\cdot(\vec{u}\cdot c) + K^{trans}VIF - K^{ep}c + v_p\partial_t VIF,$$

where c is contrast agent concentration, D is diffusion, $\vec{u}$ is velocity, K^{trans} is perfusion, K^{ep} is the return rate, and VIF is the vascular input forcing function. We then regress the terms of this PDE using a convolution of a smooth polynomial test function on each 3x3x3 window. Our method measures IFF in hydrogel with less than 10% error, and is faster than PINNs (90 s for LCFR, compared to 30 min for PINN) with comparable accuracy (17.2% error in perfusion for LCFR, 6.3% error in perfusion for PINN). Our initial studies show patients with increased variation in IFF survive 6 mo. longer than those with uniform flow ($p < 0.01$).

[1] Brown, C.E. et al. Locoregional delivery of IL-13Rα2-targeting CAR-T cells in recurrent high-grade glioma: a phase 1 trial. Nat Med 2024

[2] Cornelison, R.C et al. Convective forces increase CXCR4-dependent glioblastoma cell invasion in GL261 murine model. Sci Rep.2018

[3] Turk, O.M. et al. Delivery strategies for cell-based therapies in the brain: overcoming multiple barriers. Drug Deliv. and Transl. Res 2021

[4] Woodall RT et al. Model discovery approach enables noninvasive measurement of intra-tumoral fluid transport in dynamic MRI. APL Bioeng 2024

[5] Brummer AB, et al. Data driven model discovery and interpretation for CAR T-cell killing using sparse identification and latent variables. Front Immunol. 2023

B37 - Ensuring Real-Time Safety for Swarm Dynamics via Mean-Field Control Barrier Functions

Samy Wu Fung, Colorado School of Mines; Levon Nurbekyan, Emory University

Control Barrier Functions (CBFs) are an effective methodology to ensure safety and performative efficacy in real-time control applications such as power systems, resource allocation, autonomous vehicles, robotics, etc. This approach ensures safety independently of the high-level tasks that may have been pre-planned off-line. For example, CBFs can be used to guarantee that a vehicle will remain in its lane. However, when the number of agents is large, computation of CBFs can suffer from the curse of dimensionality in the multi-agent setting. In this work, we present Mean-field Control Barrier Functions (MF-CBFs), which extends the CBF framework to the mean-field (or swarm control) setting. The core idea is to model a population of agents as probability measures in the state space and build corresponding control barrier functions. Similar to traditional CBFs, we derive safety constraints on the (distributed) controls but now relying on the differential calculus in the space of probability measures.

B38 - Artificial Self-Insurance for Heterogeneous Households Using GQ-learning

Ivy Yang, University of Miami; Noah Williams, University of Miami

This paper introduces a novel approach for generating household-level decision rules by combining G-estimation with Reinforcement Learning. I demonstrate this method using the example of heterogeneous households' portfolio choices in response to recessional income shocks. The method indirectly estimates the law of motion while accounting for the high-dimensional macroeconomic environment by treating these shocks as time-varying factors that affect households' portfolio choices and consumption decisions differently. The Q-learning algorithm, a key Reinforcement Learning technique, is employed to recover agents' choices at each time step. G-estimation then uses these recovered choices, along with the shocks and high-dimensional macroeconomic exogenous variables, to predict subsequent state variables, guiding the learning of future choices. This iterative process recovers all agent-specific state and key choice variables over time. I evaluate the algorithm by comparing the recovered choice variables with the decision rules of a theoretical economic model, using its simulated data. Finally, the algorithm is applied to real-world panel data, recovering the choice variables of households across the wealth distribution quintiles for the year 2009. I then examine how these households make consumption and investment decisions under the influence of recessional income shocks. I find that households in the 4th and 5th quintiles of the wealth distribution actively hedge against aggregate income shocks, while those in lower cohorts tend to reduce risky asset investments to stabilize consumption when the income index is at a lower level.

B39 - Mean-field approximation for the Deffuant-Weisbuch dynamics on directed configuration model networks

Yang Yang, The Ohio State University; Joseph Tien, The Ohio State University

Deffuant-Weisbuch (DW) opinion dynamics is one of the earliest confidence-bound models where individuals update their opinions only if their current opinions are similar enough. While DW opinion dynamics on undirected networks is well understood, the number of studies examining the dynamics on directed networks is more limited. In this work, we explore the DW dynamics on a specific type of networks known as the directed configuration model networks. A mean-field approximation for this model was derived and compared to numerical simulations for directed configuration model networks of different sizes and node heterogeneity. We discuss the effect of network size and heterogeneity on the accuracy of the mean-field approximation and the opinion distribution at convergence. We also experiment with a family of initial opinion distributions and identify the region where the opinion distribution at convergence transitions from consensus to polarization.

B40 - Control of Instability in a Vlasov-Poisson System Through an External Electric Field

Yukun Yue, University of Wisconsin-Madison; Qin Li, Lukas Einkemmer, Clément Mouhot

Plasma instabilities are a major concern in plasma science, for applications ranging from particle accelerators to nuclear fusion reactors. In this work, we consider the possibility of controlling such instabilities by adding an external electric field to the Vlasov–Poisson equations. Our approach to determining the external electric field is based on conducting a linear analysis of the resulting equations. We show that it is possible to select external electric fields that completely suppress the plasma instabilities present in the system when the equilibrium distribution and the perturbation are known. In fact, the proposed strategy returns the plasma to its equilibrium at a rate that is faster than exponential in time if the Fourier transform of the initial data decays super-exponentially with respect to the Fourier variable corresponding to velocity. We further perform numerical simulations of the nonlinear two-stream and bump-on-tail instabilities to verify our theory and to compare the different strategies that we propose in this work.

B41 - Optimizing Synchronization in a Simplicial Kuramoto Model

Cameron Ziegler, SUNY Buffalo; Dane Taylor, University of Wyoming

There has been recent interest in "higher-order" extensions of the Kuramoto phase-oscillator model in which oscillators are represented by simplices in simplicial complexes (SCs) rather than vertices/nodes in graphs. In the traditional case, the synchrony alignment function (SAF) has been developed to measure and optimize the ability for a system to synchronize based on its structure and internal frequencies. We extend the SAF framework to simplicial Kuramoto models to study and optimize synchronization over SCs. Our experiments explore the balancing of upper- and lower-dimensional interactions as well as redistributing/alignment of oscillators' frequencies. Our approach involves utilizing Hodge Laplacians and investigating the role of SC homology.

B42 - A dynamical system model of gentrification: Exploring a simple rent control strategy

Jonathan Shaw, University of Colorado at Boulder; Juan G. Restrepo University of Colorado at Boulder); Nancy Rodríguez, University of Colorado at Boulder

Motivated by the need to understand the factors driving gentrification, we introduce and analyze two simple dynamical systems that model the interplay between three potential drivers of the phenomenon. The constructed systems are based on the assumption that three canonical drivers exist: a subpopulation that increases the desirability of a neighborhood, the desirability of a neighborhood, and the average price of real estate in a neighborhood. The second model modifies the first and implements a simple rent control scheme. For both models, we investigate the linear stability of equilibria and numerically determine the characteristics of oscillatory solutions as a function of system parameters. Introducing a rent control scheme stabilizes the system, in the sense that the parameter regime under which solutions approach equilibrium is expanded. However, oscillatory time series generated by the rent control model are generally more disorganized than those generated by the non-rent control model; in fact, long-term transient chaos was observed under certain conditions in the rent control case. Our results illustrate that even simple models of urban gentrification can lead to complex temporal behavior.

B43 - Age-Dependent Complexity of Locomotion in Caenorhabditis elegans

Olivia Trader, Vassar College; Dimitrios Tzepos, Vassar College; Jenny Magnes, Vassar College

Using dynamic optical diffraction, we determine how the Largest Lyapunov Exponent (LLE) changes with age in the locomotion of Caenorhabditis elegans (C. elegans). The LLE measures the divergence of a system, typically a chaotic attractor (strange attractor). A young organism tends to be more agile than its older counterparts. As the nematodes age, their neuronal circuits become less complex because their nervous system declines. C. elegans transition from egg to senility within twelve days, and like other organisms, they experience an increase and decline in motor control with age. To accurately track their age, the worms are transferred to fresh agar plates with E. coli for nutrition every two days. Data collection from day three to day twelve revealed significant findings. At three days, C. elegans exhibited a lower LLE of 1.1 ± 0.1 1/s compared to the more mature five-day-old worms with an LLE of 1.34 ± 0.08 1/s. However, a consistent decline in the LLE was observed beyond day five, with an LLE of 0.96 ± 0.03 1/s at 11 days of age. We have developed a process to show how a nematode's LLE, formally related to chaos in C. elegans, can be used to describe the complexity related to nematodes' neuronal circuits. A larger LLE implies faster changes in the locomotion than a smaller LLE. A locomotory model rendering the same LLE within the framework of a biological worm would most likely match some or all of the characteristics of a neuronal locomotor circuit of a live worm. It would lead to a deeper understanding of the locomotory driving circuit.