Dynamics Days US 2024
Presentation Titles & Abstracts

UC Davis – January 8-10, 2024

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Monday, January 8

Jan 8, Session 1, 9:00 AM - 10:30 AM

Quantifying models of biological pattern formation using topological techniques
9:00 AM - 9:30 AM (Invited)
Alexandra Volkening, Purdue University

Pattern formation is present at many scales in biology, and here I will focus on elucidating how brightly colored cells interact to form skin patterns in zebrafish. Zebrafish are named for their dark and light stripes, but mutant zebrafish feature variable skin patterns, including spots and labyrinth curves. All of these patterns form as the fish grow due to the interactions of tens of thousands of pigment cells, making agent-based modeling a natural approach for describing pattern formation. However, agent-based models are stochastic and have many parameters, so they are not analytically tractable using traditional techniques. Microscopic modeling also involves many choices beyond specifying agent interactions and setting parameter values, such as deciding whether to implement cell behavior on or off lattice and to update agents synchronously or non-synchronously. Because comparing simulated patterns and biological images is often a qualitative process, this makes it challenging to broadly characterize the output of agent-based models and identify the role of modeling choices in predictions. To help address this challenge, here I will show how to apply methods from topological data analysis to quantify cell-based, time-dynamic systems. I will overview different microscopic models and present quantitative summaries of messy cell-based patterns.

Pairing cellular and synaptic dynamics into building blocks of rhythmic neural circuits
9:30 AM - 9:50 AM (Contributed)
Andrey Shilnikov, Georgia State University

The purpose of this paper is biologically plausible modeling with conductance-based models, coupled with strength varying slow synapse models, to build up pair-wise rhythm-generating networks. We document the properties of basic network components: cell models and synaptic models, which are prerequisites for proper network assembly. Using the slow-fast decomposition we present a detailed analysis of the cellular dynamics including a discussion of the most relevant bifurcations. Several approaches to model synaptic coupling are also discussed, and a new logistic model of slow synapses is introduced. Finally, we describe and examine two types of bicellular rhythm-generating networks: i) half center oscillators ii) excitatory-inhibitory pairs and elucidate a key principle - the network hysteresis underlying the stable onset of emergent slow bursting in these neural building blocks. These two cell networks are a basis for more complicated neural circuits of rhythmogenesis and feature in our models of swim central pattern generators in two sea slugs.

A Gut Feeling: Developing a Model of Mouse Colon Motility through Data
9:50 AM - 10:10 AM (Contributed)
Andrea Welsh, University of Pittsburgh

Colon motility, the spontaneous self-generated movement and motion of the colon muscle and its cells, is produced by activity in different types of cells such as myenteric neurons of the enteric nervous system (ENS), neurons of the autonomic nervous system (ANS) and interstitial cells of Cajal (ICC). Two colon motor patterns measured experimentally are motor complexes (MC) often associated with the propulsion of fecal contents, and ripple contractions which are involved in mixing and absorption. How ICC and neurons of the ENS and ANS interact to initiate and influence colon motility is still not completely understood. This makes it difficult to develop new therapies to restore function in pathological conditions. This talk will discuss the data-driven modeling of the ICCs and neurons that also capture the global dynamics that are observed in the colon.

Emergence and coordination of stable cellular states in tissue
10:10 AM - 10:30 AM (Contributed)
Matthew Smart, Flatiron Institute

Multicellular organisms exhibit a variety of cell types supporting numerous tissue functions, yet it remains unclear how interacting cells can precisely coordinate their gene expression during tissue self-organization. We develop a generalized model of multicellular gene expression that includes intracellular and intercellular gene interactions in tissue-like collectives. We represent multistable cellular phenotypes by mapping the binarized transcriptional patterns of individual cells onto Hopfield networks, and incorporate cell-cell signaling by coupling transcriptional cell states on a graph. We show how tuning the intercellular signaling strength results in a cascade of transitions toward different collective states with emergent single-cell phenotypes. We find that disordered intercellular signaling tends to stabilize a surprisingly small number of compositionally and spatially simple tissue types. These results establish a theoretical framework to investigate how cell collectives self-organize into distinct stable patterns. Finally, we consider how these results on fixed graphs might be generalized to systems of varying topology and cell count.

Jan 8, Session 2, 10:50 AM - 12:00 PM

Towards Automated Extraction and Characterization of Scaling Regions
10:50 AM - 11:20 AM (Invited)
Elizabeth Bradley, University of Colorado Boulder

Scaling regions abound in dynamical-systems problems, such as estimation of the correlation dimension or the Lyapunov exponent. In these problems, scaling regions are generally estimated by hand, a process that is subjective and often challenging due to problems such as confirmation bias, existence of multiple scaling regions, and noise. We propose a general automated technique for extracting and characterizing scaling regions. Starting with a two-dimensional plot that may contain a scaling region, we compute an ensemble of linear fits by considering all mathematically sensible combinations of end points on the plot. Generating various distributions based on slopes from these fits, weighted by the inverse of the least squares fit error, we can determine whether or not the plot contains one or more scaling regions—or none at all. If the results suggest the existence of scaling regions, these distributions give their slopes and extents. We also offer statistical error bars for the results. For the correlation dimension estimation problem, we demonstrate the reliability of this method using various well-known dynamical systems. We also show that the ensemble method can be extended to other problems in dynamical systems (such as parameter selection in delay-coordinate embedding) and other areas outside dynamical systems as well (e.g. estimating the exponent of a power law distribution).

Spatial and temporal cluster tomography
11:20 AM - 11:40 AM (Contributed)
István Kovács, Northwestern University

As we address systems of increasing complexity, it becomes ever more challenging to identify the relevant order parameters to characterize different phases and the corresponding transitions, especially in systems out-of-equilibrium. At the same time, pattern formation in complex systems often leads to distinct clusters or regions. The emerging cluster structures span from magnetic domains in classical and quantum systems through flocks and motility-induced phase separation in active matter, and even brain regions. Here, we discuss the concept of cluster tomography, a simple and efficient geometric approach to detect phase transitions and characterize the universality class in any classical or quantum system with a relevant cluster structure, both in- and out-of-equilibrium.

In the simplest application of spatial cluster tomography, we consider the number of clusters $N(L)$ intersected by a line of length L. As expected, to leading order, $N(L) = aL$, where a depends on the microscopic details. In this talk, we will show that in a broad range of classical and quantum systems [1, 2], critical points are indicated by an additional nonlinearity in the form of $b\ln(L)$, where b is universal. In 2d, our findings are further supported by analytic results in conformally invariant systems [3]. We also discuss the analogous concept of temporal cluster tomography, motivated by the concept of burstiness in complex network dynamics. These methods are just two aspects of a unified cluster tomography framework, characterizing the geometric complexity of a system via the statistics of low-dimensional cross-sections, akin to a geometric notion of susceptibility.

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Community assembly via invasion graphs: Mathematical rigor meets empirical realism
11:40 AM - 12:00 PM (Contributed)
Sebastian Schreiber, University of California, Davis

Community assembly is the study of ecological processes that determine the species composition of ecological communities. One conceptualization of community assembly is rare invasions of species from a regional pool into a focal area. Successful invasions will shift the local community from one configuration of species to another configuration. In this talk, I will introduce a mathematically rigorous framework for representing the process of community assembly. This framework builds on work with Josef Hofbauer on invasion graphs for Lotka-Volterra models. The vertices of these invasion graphs corresponds to equilibria of the Lotka-Volterra models and directed edges correspond, roughly, to potential connecting orbits between pairs of equilibria. Under appropriate assumptions, these invasion graphs determine which equilibria correspond to permanent communities. I will show how an appropriate pruning of these invasion graphs yields community assembly graphs (CAGs). that represent the community assembly process. To illustrate their utility, I compute CAGs for 35 empirically parameterized Lotka-Volterra models of 3 to 13 interacting species. Analyzing these empirically derived CAGs, I address several fundamental questions in community ecology: How often does community assembly lead to a single end state, multiple end states, or endless cycling? What is the relationship between regional species richness and local community richness? How many paths are there to end states and what is the distribution of their lengths? Future directions and open questions will be discussed.

Jan 8, Session 3, 2:10 PM - 3:40 PM

Equations as emergent phenomena determined using machine learning: An ocean case study
2:10 PM - 2:40 PM (Invited)
Maike Sonnewald, UC Davis

The Southern Ocean, surrounding the Antarctic continent, closes the global overturning circulation and is key to the regulation of carbon and heat, biological production, and sea level. However, the dynamics of the general circulation remain poorly understood. Here, a unifying framework is proposed by determining governing equations as emergent properties using a pioneering machine learning inference methodology. A semi-circumpolar 'supergyre' north of the Antarctic continent is proposed: a massive series of ?leaking?sub-gyres that are connected and maintained via rough topography that acts as scaffolding. The supergyre framework challenges the conventional view of having separate circulation structures in the Weddell and Ross seas and suggests a limited utility for climate applications of idealized models and conventional zonal averaged frameworks. Machine learning was used to reveal areas of coherent driving forces within a vorticity-based analysis. Predictions from the supergyre framework are supported by available observations and could aid observational and modelling efforts of the climatically key region undergoing rapid change.

Nowcasting Earthquakes with QuakeGPT: An Earthquake Generative Pretrained Transformer
2:40 PM - 3:00 PM (Contributed)
John Rundle, University of California

We are developing a new approach to earthquake nowcasting based on science transformers (GC Fox et al., Geohazards, 2022). As explained in the seminal paper by Vaswani et al. (NIPS, 2017), a transformer is a type of deep learning model that learns the context of a set of time series values by means of tracking the relationships in a sequence of data, such as the words in a sentence. Transformers extend deep learning in the adoption of a context-sensitive protocol "attention", which is used to tag important sequences of data, and to identify relationships between those tagged data. Pretrained transformers are the foundational technology that underpins the new AI models ChatGPT (Generative Pretrained Transformers) from openAI.com, and Bard, from Google.com. In our case, we hypothesize that a transformer might be able to learn the sequence of events leading up to a major earthquake. Typically, the data used to train the model is in the billions or larger, so these models, when applied to earthquake problems, need the size of data sets that only long numerical earthquake simulations can provide. In this research, we are developing the Earthquake Generative Pretrained Transformer model, "QuakeGPT", in a similar vein. For simulations, we are using long simulation catalogs from a physics-informed statistical model of earthquakes, the Epidemic Type Aftershock Sequence model. We will also use the physics-based model Virtual Quake model, and a statistical physics model based on invasion percolation. Observed data, which is the data to anticipate with nowcasting, is taken from the USGS online catalog for California. In this talk, we discuss the architecture of QuakeGPT and report first results.

Machine learning of model errors in dynamical systems
3:00 PM - 3:20 PM (Contributed)
Matthew Levine, Broad Institute

The development of data-informed predictive models for dynamical systems is of widespread interest in many disciplines. Here, we present a unifying framework for blending mechanistic and machine-learning approaches for identifying dynamical systems from data. This framework is agnostic to the chosen machine learning model parameterization, and casts the problem in both continuous- and discrete-time. We will also show recent developments that allow these methods to learn from noisy, partial observations. We first study model error from the learning theory perspective, defining the excess risk and generalization error. For a linear model of the error used to learn about ergodic dynamical systems, both excess risk and generalization error are bounded by terms that diminish with the square-root of T (the length of the training trajectory data). In our numerical examples, we first study an idealized, fully-observed Lorenz system with model error, and demonstrate that hybrid methods substantially outperform solely data-driven and solely mechanistic-approaches. Then, we present recent results for modeling partially observed Lorenz dynamics that leverages both data assimilation and neural differential equations.

Data-Driven Inference of Reduced Order Models for Strongly Perturbed Limit Cycle Oscillators 3:20 PM - 3:40 APM (Contributed)
Dan Wilson, University of Tennessee

Phase–amplitude reduction (a general extension of phase reduction developed by Kuramoto and Winfree) have shown great promise for identifying analytically tractable reduced order models in applications involving strongly perturbed and strongly coupled oscillatory dynamical systems. However, efficient and accurate methods for inference of these reduced order models from data are still needed. In this talk, I will discuss two recently developed data-driven strategies for inferring reduced order models for general oscillatory systems from time-series data. These approaches can be readily implemented in situations where full state measurements are unavailable and does not require any knowledge of the underlying model equations. In applications involving control of both circadian and neural rhythms, the proposed approaches outperform standard phase-based reductions and other state-of-the-art Koopman-based model identification techniques.

Jan 8, Session 4, 4:30 PM - 5:30 PM

How Ignition and Target Gain > 1 were achieved in inertial fusion
4:30 PM - 5:00 PM (Invited)
Omar Hurricane LLNL

For many decades, the running joke in fusion research has been that 'fusion' is twenty years away and always will be. Yet, this year we find ourselves in a position where we can talk about the milestones of burning plasmas, fusion ignition, and target energy gain greater than unity in the past tense. Fusion is no longer a joke! In this talk, I tell the story of the applied physics challenges that needed to be overcome to achieve these milestones and the strategy our team followed. To help understand the story, several key physics principles of inertial fusion will be presented, and I will try and dispel any confusion about what the terms burning, ignition, and gain mean in the context of inertial fusion research.

*Work performed under the auspices of the U. S. Department of Energy by LLNL under contract DE-AC52-07NA27344

Climate Meets Complex Systems: Exploring Teleconnections in the Climate System via a Complex Network Approach
5:00 PM - 5:30 PM (Invited)
Jurgen Kurths Humboldt University

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. After introducing physical models for weather forecast already in 1922 by L.F. Richardson, a fundamental open problem has been the understanding of basic physical mechanisms and exploring anthropogenic influences on climate. In 2021 Hasselmann and Manabe got the Physics Nobel Price for their pioneering works on this. I will shortly review their main seminal contributions and discuss most recent challenges concerning climate change. Next, I will introduce a recently developed approach via complex networks mainly to analyze long-range interactions in the climate system. This leads to an inverse problem: Is there a backbone-like structure underlying the climate system? To treat this problem, we have proposed a method to reconstruct and analyze a complex network from spatio-temporal data. This approach enables us to uncover teleconnections among tipping elements, in particular between Amazon Rainforest and the Tibetan Plateau, but also between the Arctic and Southwest China and California. Implications of these findings are discussed.

Tuesday, January 9

Jan 9, Session 1, 9:00 AM - 10:30 AM

Why dynamics matter for data assimilation with sparse physiological data
9:00 AM - 9:30 AM (Invited)
Dave Albers Univ of Colorado School of Medicine

Data assimilation has been used to accurately estimate dynamical systems with data when these systems are well measured, supporting novel and impactful model-based forecasting. In the context of human physiology, the most realistic and expansive data sets are measured in clinical settings where measurement is difficult, sparse, and often minimized. Moreover, in addition to being a massive source of data, the use of physiological modeling within biomedicine has the potential to transform medicine. However, in real world settings, human physiological dynamics are complex, oscillatory, and non-stationary. And, while this situation is exactly the type of setting data assimilation was designed to address, the combination of complex, nonstationary dynamics with sparse data can lead to comically impressive pathological model estimation problems being common. Such problems severely imped the use of data assimilation for both scientific and practical ends in the context of clinically collected, real-world data. This talk will start with demonstrative examples and can be used to understand the sources of these particularly vexing model estimation problems. These examples will be followed with some partial solutions and proposed open problems. Along the way, I will discuss some roadblocks to advancement, including barriers that have hindered the interdisciplinary collaborations that will provide more lasting solutions and deep wells of new and impactful dynamics problems.

Delay Induced Swarm Pattern Bifurcations in Mixed Reality Experiments
9:30 AM - 9:50 AM (Contributed)
Ioana Triandaf, Naval Research Laboratory

Our work provides a model for swarming behavior of coupled mobile agents with communication-time delay which exhibits multiple dynamic patterns in space, which depend on interaction strength and communication delay. The model is created based on statistical mechanics principles so it applies to large numbers of networked agents. A thorough bifurcation analysis has been carried out to explore parameter regions where various patterns occur. We extend this work to robotics applications by introducing a mixed-reality framework in which real and simulated robots communicate in real time creating the self-organized states predicted by the theory. Mixed reality retains the key features of physical experiments that are hard to capture through simulation alone. The proposed swarm controller was tested on two different robotic platforms: NRL's autonomous air vehicles and UPENN's micro-autonomous surface vehicles on water. A careful bifurcation picture of the swarm dynamic patterns is compared between theory and experiment as a function of attraction strength and delay. Our experimental results led to further development of the theory in order to explain observed experimental behaviors such as bi-stability of swarm patterns, not predicted by the mean-field model.

Discovering dynamics and parameters of nonlinear oscillatory and chaotic systems from partial observations
9:50 AM - 10:10 AM (Contributed)
George Stepaniants, Massachusetts Institute of Technology

Complex multi-component systems from cells and tissues to biochemical reactors often exhibit oscillatory and chaotic nonlinear dynamics that are essential to their signaling properties and functions. Despite the rapid advancement of sensor and imaging technology, many physical and biological systems can only be partially observed with practitioners in need of model-fitting tools that can account for this missing information. Here we develop an automated inference method that discovers predictive differential equation models from a few noisy partial observations of a system's state. We illustrate our method on a combination of both simulation and experimental data from a variety of physical, chemical and biological systems showing that in many cases noisy partial observations are sufficient to infer predictive multivariate dynamical systems.

Optimized measurements of chaotic dynamical systems via the information bottleneck
10:10 AM - 10:30 AM (Contributed)
Kieran Murphy, University of Pennsylvania

Deterministic chaos permits a precise notion of a "perfect measurement" as one that, when obtained repeatedly, captures all of the information created by the system's evolution with minimal redundancy. Finding an optimal measurement is challenging, and has generally required intimate knowledge of the dynamics in the few cases where it has been done. We establish an equivalence between a perfect measurement and a variant of the information bottleneck. As a consequence, we can employ machine learning to optimize measurement processes that efficiently extract information from trajectory data. We obtain approximately optimal measurements for multiple chaotic maps and lay the necessary groundwork for efficient information extraction from general time series.

Jan 9, Session 2, 10:50 AM - 12:20 PM

Harnessing chaos for generative modeling in the brain
10:50 AM - 11:20 AM (Invited)
Rishi Chaudhuri UC Davis

Chaos is generic in strongly-coupled recurrent networks of model neurons, and thought to be a common dynamical regime in the brain. While neural chaos is typically seen as an impediment to be overcome, we show how such chaos might play a functional role in allowing the brain to learn and sample from generative models of the world. The ability to build such generative models is thought to be crucial to flexible intelligence. We construct model architectures that combine classic models of neural chaos with canonical generative modeling architectures and show that they have a number of appealing properties, including easy biologically-plausible control of sampling rates.

Network-Motif Delay Differential Analysis of Brain Activity During Seizures
11:20 AM - 11:40 AM (Contributed)
Claudia Lainscsek, Salk Institute/UCSD

Epilepsy is a neural network disorder that affects over fifty million people worldwide. Although some patients benefit from current medical treatments, many still have seizures that are refractory. Despite advances made in the diagnosis and treatment of epilepsy, the proportion of patients who are free of seizures following treatment has not changed. Epilepsy manifests in a wide range of symptoms and conditions, with influence that often extends far beyond the regions of seizure onset. Recent methods aimed at uncovering the network dynamics of brain activity allow seizures to be investigated in ever greater detail. Here we use Network-Motif DDA (NM-DDA), a new flavor of delay-differential analysis (DDA), to explore and better understand how seizures originate, the pathways through which they propagate, and how they eventually terminate.

We first test the capabilities of NM-DDA on simulated data of the Rössler system under different parameter regimes and noise conditions. We then apply NM-DDA to invasive intracranial electroencephalographic (iEEG) data from drug-resistant epilepsy patients undergoing presurgical monitoring. The directional network motifs between brain areas that emerge from this analysis change dramatically before, during, and after seizures. These new analytical techniques have the potential to enhance clinical practice in epilepsy diagnostics and to develop a novel seizure classification system. This would provide us with a greater understanding of different seizures and bring us a step closer to providing patient-specific treatments for controlling an individual's epilepsy.

Coarse-grained models of cortical circuits
11:40 AM - 12:00 PM (Contributed)
Kevin Lin, University of Arizona

Biologically realistic models in neuroscience are challenging to build and to simulate due to the large numbers of neurons, their complex interactions, and the large number of unknown physiological parameters. Reduced, or coarse-grained, models are more tractable, but it is not always clear how to evaluate results produced by models that are too far removed from neuroanatomy & physiology. In this talk, I will describe a recently proposed approach to coarse-graining cortical models that aims to balance biological realism and computational efficiency. I will illustrate how the strategy can be used to (i) map out the space of "viable" parameters for a model of the Macaque primary visual cortex; and (ii) reproduce the orientation selectivity properties of the primate primary visual cortex.

Complex localization mechanisms in networks of coupled oscillators: two case studies
12:00 PM - 12:20 APM (Contributed)
Zachary Nicolaou, University of Washington

Localized phenomena abound in nature and throughout the physical sciences. Some universal mechanisms for localization have been characterized, such as in the snaking bifurcations of localized steady states in pattern-forming partial differential equations. While much of this understanding has been targeted at steady states, recent studies have noted complex dynamical localization phenomena in systems of coupled oscillators. These localized states come in the form of symmetry-breaking chimera patterns that exhibit a coexistence of coherence and incoherence in symmetric networks of coupled oscillators. Here, we report detailed numerical continuations of localized time-periodic states in systems of coupled oscillators, while also documenting the numerous bifurcations they give way to. We find novel routes to localization involving bifurcations of heteroclinic cycles in networks of Janus oscillators and strange bifurcation diagrams resembling chaotic tangles in a parametrically driven array of coupled pendula. We highlight the important role of discrete symmetries and the symmetric branch points that emerge in symmetric models.

Jan 9, Session 3, 2:30 PM - 4:00 PM

Predicting tipping point with machine learning
2:30 PM - 3:00 PM (Invited)
Ying-Cheng Lai Arizona State University

There has been a growing interest in exploiting machine learning to predict the behaviors of complex and nonlinear dynamical systems. A problem is to predict a tipping point at which the system undergoes a transition from a functioning steady state to a collapsing steady state. From the dynamical point of view, a tipping point is triggered by an inverse saddle-node bifurcation, at which a healthy steady state is destroyed, leaving a catastrophic or an extinction steady state as the only attractor of the system. Compared with the existing works on model-free prediction of chaotic systems, to predict a tipping point is significantly more challenging, because the training data are from the system when it is in a steady state. The speaker will describe the tipping-point mechanism including a recent theory for rate-induced tipping, discuss how dynamical noise can be exploited in machine learning to predict the future occurrence of a tipping point, and present benchmark examples as well as a real-world application.

Statistics of Attractor Embeddings in Reservoir Computing
3:00 PM - 3:20 PM (Contributed)
Louis M Pecora, University of Maryland

A recent branch of AI or Neural Networks that can handle time-varying signals often in real time has emerged as a new direction for signal analysis. These dynamical systems are usually referred to as reservoir computers. A central question in the operation of these systems is whether a reservoir computer (RC) when driven by only one time series from a driving or source system is internally recreating all the drive dynamics or attractor itself., i.e. an embedding of the drive attractor in the RC dynamics. There are some mathematical advances that move that argument closer to a general theorem. However, for RCs constructed from actual physical systems like interacting lasers or analog circuits, the RC dynamics may not be known well or at all. We present a statistic that can help test for homeomorphisms between a drive system and the RC by using the time series from both systems. This statistic is called the continuity statistic and it is modeled on the mathematical definition of a continuous function. We show the interplay of dynamical quantities (e.g. Lyapunov exponents, Kaplan-Yorke dimensions, generalized synchronization, etc.) and embeddings as exposed by the continuity statistic and other statistics based on ideas from nonlinear dynamical systems theory. These viewpoints and results lead to a clarification of various currently vague concepts about RCs, such as fading memory, stability, and types of dynamics that are useful.

Controlling dynamical systems to arbitrary target states using classical-, next-generation- and the new minimal reservoir computing
3:20 PM - 3:40 PM (Contributed)
Alexander Haluszczynski, Risklab, Allianz Global Investors

Utilizing machine learning to control nonlinear dynamical systems not only enables the imposition of simple behavior such as periodicity but also to drive the system into more intricate, arbitrary dynamics [1]. The key lies in the machine learning system's capacity to replicate the desired dynamics. To showcase this concept, we control a chaotic parametrization of the Lorenz system into intermittent dynamics.
We start by employing classical reservoir computing (RC) and confirm its performance in this task. Subsequently, we conducted a comparative analysis with varying amounts of training data, benchmarking classical reservoir computing [2], [3] against next-generation reservoir computing [4], [5] as well as a newly presented approach called "minimal reservoir computing" [6]. The latter is characterized by a simplified architecture, which is further minimizing computational resources.
Our results demonstrate that, particularly in situations where data is scarce, both next-generation and minimal reservoir computing outperform classical reservoir computing, leading to a substantial enhancement in performance. In particular, the performance of minimal reservoir computing is comparable to next-generation reservoir computing. Given the advantages of minimal reservoir computing in the context of hardware implementations, this makes it an appealing choice for practical control applications in real-world scenarios with restricted access to data.
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Suppressing unknown disturbances to dynamical systems using machine learning
3:40 PM - 4:00 PM (Contributed)
Juan G. Restrepo, University of Colorado at Boulder

Identifying and suppressing unknown disturbances to dynamical systems is a problem with applications in many different fields. We present a model-free method to identify and suppress an unknown disturbance to an unknown system based only on previous observations of the system under the influence of a known forcing function. We find that, under very mild restrictions on the training function, our method is able to robustly identify and suppress a large class of unknown disturbances. We illustrate our scheme with the identification of unknown forcings to an analog electric chaotic circuit and with a numerical example where a chaotic disturbance to the Lorenz system is identified and suppressed.

Wednesday, January 10

Jan 10, Session 1, 9:00 AM - 10:30 AM

Universal aspects of cardiac dynamics
9:00 AM - 9:30 AM (Invited)
Leon Glass McGill University

One approach to achieve an understanding of cardiac rhythms involves development of "accurate" anatomical and ionic models of cardiac tissue and determining the properties by computer simulation. An alternative approach, that I will discuss, involves extracting key features that must necessarily arise in systems of spontaneous pacemakers (e.g. the sinus node or ectopic foci) embedded in an excitable medium (the myocardium). I will consider three different problems all of which arise in both experimental and clinical settings: (i) rhythms arising from two pacemakers embedded in cardiac tissue; (ii) analysis of situations in which the action potential duration alternates from beat to beat; (iii) spontaneous termination of reentrant arrhythmia. In each case, experiments can be designed to demonstrate the phenomena and the observed dynamics can be understood using techniques from nonlinear dynamics. The mathematical perspective offers new approaches for diagnosis and control of these arrhythmias.

Emergent node hierarchy in a centrality-based preferential attachment model
9:30 AM - 9:50 AM (Contributed)
Anastasiya Salova, Northwestern University

Preferential attachment is a plausible mechanism of generating some of the network properties observed across domains, such as the approximately scale-free degree distribution and the presence of high-degree hubs. However, in traditional preferential attachment models, the node degree evolution is determined solely by the time a node is attached to the network, and no other details of the network structure, e.g., the identity and degrees of its neighbors, affect its future degree [1,2]. Such details are expected to be important in some real-life scenarios, such as the growth of scientific collaboration networks. There, scientists can make informed decisions on which collaborations to form with the goal of improving their own prospects using information beyond the node degree [3].

To take more information into account in the growth process, we introduce a centrality-based preferential attachment model, where the connection probability is proportional to the prospective neighbor's eigenvector centrality. We find that this model has several remarkable properties. For instance, a hierarchy of nodes gets established early on. The dominant node, which is defined by having the highest degree and centrality, evolves with the highest dynamical exponent. Its neighbors' exponent is lower, but they still gain an advantage in their rate of accumulating neighbors compared to the rest of the nodes in the network. In other words, the evolution of a given node's degree is strongly influenced by its location in the network and the identity of its neighbors. The distribution of node centralities supports this division of nodes into distinct emergent classes determined by their distance from the dominant node. This hierarchy is also evident from the plateaus of the resulting degree distribution. We close by discussing how to formalize the phenomena we observe more generally and how to link them to real-life network data.

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Contagion dynamics on hypergraphs with nested hyperedges
9:50 AM - 10:10 AM (Contributed)
Kwang-Il Goh, Korea University

In complex social systems encoded as hypergraphs, higher-order (i.e., group) interactions taking place among more than two individuals are represented by hyperedges. One of the higher-order correlation structures native to hypergraphs is the nestedness: Some hyperedges can be entirely contained (that is, nested) within another larger hyperedge, which itself can also be nested further in a hierarchical manner. Yet the effect of such hierarchical structure of hyperedges on the dynamics has remained unexplored. In this context, here we propose a random nested-hypergraph model with a tunable level of nestedness and investigate the effects of nestedness on a higher-order susceptible-infected-susceptible process. By developing an analytic framework called the facet approximation, we obtain the steady-state fraction of infected nodes on the random nested-hypergraph model more accurately than existing methods. Our results show that the hyperedge-nestedness affects the phase diagram significantly. Monte Carlo simulations support the analytical results. This presentation is based on the work published in Kim et al. Phys. Rev. E 108, 034313 (2023).

Deeper but smaller: Higher-order interactions increase linear stability but shrink basins
10:10 AM - 10:309 AM (Contributed)
Yuanzhao Zhang, Santa Fe Institute

A key challenge of nonlinear dynamics and network science is to understand how polyadic couplings influence collective behavior in complex systems. In this talk, I will show that the effects of higher-order interactions can be multifaceted by analyzing the dynamical patterns of identical Kuramoto oscillators on hypergraphs. In particular, higher-order interactions can have opposite effects on linear stability and basin stability, stabilizing twisted states by improving their linear stability, but also dramatically reducing their basin sizes, making them hard to find from random initial conditions.

Jan 10, Session 2, 10:50 AM - 12:00 PM

Evolutionary Dynamics Within and Among Competing Groups
10:50 AM - 11:20 AM (Invited)
Daniel Cooney, University of Illinois Urbana-Champaign

Biological and social systems are structured at multiple scales, and the incentives of individuals who interact in a group may diverge from the collective incentive of the group as a whole. Mechanisms to resolve this tension are responsible for profound transitions in evolutionary history, including the origin of cellular life, multicellular life, and even societies. In this talk, we synthesize a growing literature that extends evolutionary game theory to describe multilevel evolutionary dynamics, using nested birth–death processes and partial differential equations to model natural selection acting on competition within and among groups of individuals. We analyze how mechanisms known to promote cooperation within a single group—including assortment, reciprocity, and population structure—alter evolutionary outcomes in the presence of competition among groups. We find that population structures most conducive to cooperation in multiscale systems can differ from those most conducive within a single group. Likewise, for competitive interactions with a continuous range of strategies we find that among-group selection may fail to produce socially optimal outcomes, but it can nonetheless produce second-best solutions that balance individual incentives to defect with the collective incentives for cooperation. We conclude by describing the broad applicability of multiscale evolutionary models to problems ranging from the production of diffusible metabolites in microbes to the management of common-pool resources in human societies.

Understanding Polarization In the Higher Order Non-Linear Voter Model
11:20 AM - 11:40 AM (Contributed)
Will Thompson, University of Vermont

Polarization is a pervasive societal issue, demanding insight into its origins. The non-linear voter model, explaining polarization through local interactions, traditionally focuses on pairwise networks, neglecting group-level dynamics. This study presents a minimal extension of the non-linear voter model to encompass higher-order networks and group effects.

In our model, nodes belong to social cliques representing interaction groups. As nodes engage with more cliques, interdependence among group dynamics grows. A parameter, q, introduces nonlinearity; $q = 1$ corresponds to the linear voter model, while $q > 1$ amplifies conformity, and $q < 1$ diminishes it.

To investigate system dynamics, we employ approximate master equations (AMEs) and probability-generating functions, unveiling the model's asymptotic behavior in the thermodynamic limit. Through analytical and numerical methods, we delineate phases of the system based on model parameters, q, conformity bias, and group coupling strength. These phases encompass consensus, coexistence, and a unique bimodal consensus.

Notably, this study reveals a unique bimodal consensus phase, combining high couplings with an anti-conformity bias, supports the existence of stable minorities within cliques. We describe phase transitions and demonstrate that heterogeneous group sizes foster coexistence at lower coupling strengths. Finally, we compare our results with a non-linear voter model on a pairwise network to demonstrate the importance of higher-order effects to our results.

This research bridges the gap between voter model theory and higher-order networks, shedding light on the factors facilitating or impeding the coexistence of diverse viewpoints.

Modeling misperception of public support for climate policy
11:40 AM - 12:00 PM (Contributed)
Ekaterina Landgren, University of Colorado Boulder

Mitigating the consequences of climate change and reducing political polarization are two of the biggest problems facing society today. These problems are intertwined, since meeting international climate-mitigation targets requires implementing policies that accelerate the rate of decarbonization, and these policies can succeed only with widespread bipartisan support. Since the late 1980s, climate change has become a strongly polarizing issue in the United States. However, overall support for climate policy is high, with 66-80% of Americans supporting climate policies. Curiously, 80-90% of Americans underestimate public support for these policies, estimating the prevalence of support to be as low as 37-43%. (Sparkman et al. Nature communications 13.1 (2022): 4779.) The implications of such widespread misperception range from individual behaviors to legislative outcomes. Supporters of climate policy are more likely to self-silence if they believe their peers do not support it, and politicians are less likely to promote policies they believe to be unpopular. Here we present an agent-based social-network model of public perception of support for climate policy grounded in previous empirical studies and opinion surveys. We find that homophily effects alone do not explain widespread misperception. However, our network analysis suggests that disproportionate representation of opposition to climate policy among central nodes can offer a potential explanation for underestimation of public support. In order to assess the validity of this assumption in the real world, we explore the coverage of climate policy in U.S. news media in order to inform our model.

Jan 10, Session 3, 2:10 PM - 3:40 PM

Accurate numerical computations of spiral spectra using exponentially weighted spaces
2:10 PM - 2:40 PM (Invited)
Stephanie Dodson, Colby College

Spiral waves patterns are commonly modeled by reaction-diffusion equations and their linear stability can be probed by computing the spectra of the operator linearized about the pattern. However, this process can be numerically challenging. It is known that when an operator is posed on a spatially extended domain, the norm of the resolvent can grow exponentially with the size of the domain, leading to numerical instabilities and large pseudospectra bounds. This fact has been previously studied in the convection-diffusion operator, but the operators from spiral waves are no different. Thus, when applied to spiral wave problems, standard sparse eigenvalue algorithms result in inaccurate and spurious results. In this work, we show that the resolvent norm of spiral wave operators can be bounded by considering the operator in an exponentially weighted space, with the exponential weight derived from the spatial eigenvalues of the asymptotic linearized operator. We demonstrate numerically how the exponential weight stabilizes eigenvalue computations and allows the spectra of relevant spiral wave operators to be efficiently computed using sparse matrix methods. Both the convection-diffusion operator and spiral waves in the Barkley model are used to showcase this phenomenon.

Controlling chaotic advection in 2D active nematic materials
2:40 PM - 3:00 PM (Contributed)
Kevin Mitchell, University of California, Merced

Recent years have seen a surge of interest in active materials, in which energy injected at the microscale gives rise to mesoscale coherent motion. One prominent example is an active 2D "liquid crystal" composed of microtubules in the nematic phase. The activity is generated by molecular motors that consume ATP to generate local shearing between the microtubules. The resulting 2D fluid flow exhibits self-generated mesoscale chaotic dynamics with a characteristic folding and stretching pattern. It is a laboratory paradigm for chaotic advection and topological dynamics, in which the fluid can be viewed as "stirred" by topological defects in the nematic order parameter. Typically, these defects move in an irregular, chaotic pattern. Here, we explore conditions, both theoretically and in experiments, under which the topological defects can be coaxed to perform regular periodic motion, thus bringing some degree of order to the chaos. Throughout, we analyze the degree of mixing via the topological entropy and Lyapunov exponent of the flow and relate these quantities to the braiding of topological defects about one another.

Mathematical Modeling of Word-Meaning Association
3:00 PM - 3:20 PM (Contributed)
Deborah Tonne, UC Irvine

Primates communicate via proto-typical innate calls and composite "words" that contain combinations of such calls. In this work, we study the emergence of these new words and how the population's language reacts to such innovations. We have created a stochastic agent-based model to describe the process of learning in a population and a system of ODEs that captures important properties of this system. Using both numerical simulations and analyses of the ODEs we investigated situations where a new word is introduced to a population. Our results for a two-word two-event system, where an event represents a unique word-meaning association, indicate the ability of individuals to regularize linguistic input is at the core of the population's ability to form and maintain a shared language. We find that higher degrees of regularization ability, as well as a more balanced relative frequencies of the two events result in a language where event-word pairs are deterministic and non-ambiguous.

Cyber-physical attacks on coupled phase oscillators
3:20 PM - 3:40 PM (Contributed)
Melvyn Tyloo, Los Alamos National Laboratory

For many coupled dynamical systems, the interaction is the outcome of the measurement that each unit has of the others as e.g. in modern inverter-based power grids, autonomous vehicular platoons or swarms of drones, or it is the result of physical flows. Synchronization among all the components of these systems is of primal importance to avoid failures. The overall operational state of these systems therefore crucially depends on the correct and reliable functioning of the individual elements as well as the information they transmit through the network. In this talk, we are going to discuss both physical perturbations and cyber attacks. In both cases, we assess the impact on the global collective behavior of nonlinearly coupled phase oscillators. We relate the synchronization error induced by the input signal to the properties of the attacked/perturbed node. This allows to anticipate the potential of an attacker or a physical perturbation and identify which network components to secure.

Jan 10, Session 4, 4:10 PM - 5:10 PM

Collisions of localized patterns in a nonvariational Swift-Hohenberg equation

4:10 PM - 4:30 PM (Contributed)

Adrian van Kan, University of California at Berkeley

The cubic-quintic Swift-Hohenberg equation (SH35) has been proposed as an order parameter description of several convective systems with reflection symmetry in the layer midplane, including binary fluid convection. We use numerical continuation, together with extensive direct numerical simulations (DNSs), to study SH35 with an additional nonvariational quadratic term to model the effects of breaking the midplane reflection symmetry. The nonvariational structure of the model leads to the propagation of asymmetric spatially localized structures (LSs). An asymptotic prediction for the drift velocity of such structures, derived in the limit of weak symmetry breaking, is validated numerically. Next, we present an extensive study of possible collision scenarios between identical and nonidentical traveling structures, varying a temperature-like control parameter. These collisions are inelastic and result in stationary or traveling structures. Depending on system parameters and the types of structures colliding, the final state may be a simple bound state of the initial LSs, but it can also be longer or shorter than the sum of the two initial states as a result of nonlinear interactions. The Maxwell point of the variational system, where the free energy of the global pattern state equals that of the trivial state, is shown to have no bearing on which of these scenarios is realized. Instead, we argue that the stability properties of bound states are key. While individual LSs lie on a modified snakes-and-ladders structure in the nonvariational SH35, the multipulse bound states resulting from collisions lie on isolas in parameter space, disconnected from the trivial solution. In the gradient SH35, such isolas are always of figure-eight shape, but in the present nongradient case they are generically more complex, although the figure-eight shape is preserved in a small subset of cases. Some of these complex isolas are shown to terminate in T-point bifurcations. A reduced model is proposed to describe the interactions between the tails of the LSs. The model consists of two coupled ordinary differential equations (ODEs) capturing the oscillatory nature of SH35 profiles at the linear level. It contains three parameters: two interaction amplitudes and a phase, whose values are deduced from high-resolution DNSs using gradient descent optimization. For collisions leading to the formation of simple bound states, the reduced model reproduces the trajectories of LSs with high quantitative accuracy. When nonlinear interactions lead to the creation or deletion of wavelengths, the model performs less well. Finally, we propose an effective signature of a given interaction in terms of net attraction or repulsion relative to free propagation. It is found that interactions can be attractive or repulsive in the net, irrespective of whether the two closest interacting extrema are of the same or opposite signs. Our findings highlight the rich temporal dynamics described by this bistable nonvariational SH35 and show that the interactions in this system can be quantitatively captured, to a significant extent, by a highly reduced ODE model.

Universal Dynamical Computing on the Nanoscale

4:30 PM - 4:50 PM (Contributed)

Christian Pratt, University of California-Davis

Conventional computational systems operate more inefficiently than what is theoretically possible according to Landauer's principle. To overcome these deficiencies, investigating unconventional computational substrates provides insight into the fundamental thermodynamic limits of computation. Dynamical computing is a computational paradigm which leverages the tools of nonlinear dynamical systems theory to realize computations. Crucially, this approach permits a geometrical interpretation of computation that would otherwise be inaccessible. As a prototypical example, inductively coupling two variable β rf superconducting quantum interference devices (vβ-rf SQUIDs) generates a thermodynamic system containing actionable informational states which are controlled by energetic and entropic transformations, and whose dynamics support information storage and processing. Through the lens of fixed point and bifurcation classifications, we demonstrate that this system is capable of executing universal logic gates via suitable circuit parameter ranges and physically motivated control protocols. With this, future comparisons regarding thermodynamic efficiencies of executing ubiquitous universal computations, e.g. NAND, can be made with conventional computational systems to ultimately gauge their thermodynamic performances.

From Stability to Chaos: Analyzing Gradient Descent Dynamics in Quadratic Regression

4:50 PM - 5:10 PM (Contributed)

Krishna Balasubramanian, Department of Statistics, UC Davis

We conduct a comprehensive investigation into the dynamics of gradient descent using large-order constant step-sizes in the context of quadratic regression models. Within this framework, we reveal that the dynamics can be encapsulated by a specific cubic map, naturally parameterized by the step-size. Through a fine-grained bifurcation analysis concerning the step-size parameter, we delineate five distinct training phases: (1) monotonic, (2) catapult, (3) periodic, (4) chaotic, and (5) divergent, precisely demarcating the boundaries of each phase. As illustrations, we provide examples involving phase retrieval and two-layer neural networks employing quadratic activation functions and constant outer-layers, utilizing orthogonal training data. Our simulations indicate that these five phases also manifest with generic non-orthogonal data. We also empirically investigate the generalization performance when training in the various non-monotonic (and non-divergent) phases. In particular, we observe that performing an ergodic trajectory averaging stabilizes the test error in non-monotonic (and non-divergent) phases.