Dynamics Days 2024
Invited speaker abstracts

Dave Albers

"Why dynamics matter for data assimilation with sparse physiological data"

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.

Liz Bradley

"Towards Automated Extraction and Characterization of Scaling Regions"

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).

Rishidev Chaudhuri
"Harnessing chaos for generative modeling in the brain"

Abstract: 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.

Daniel Cooney
"Evolutionary Dynamics Within and Among Competing Groups"

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.

Stephanie Dodson
"Accurate numerical computations of spiral spectra using exponentially weighted spaces"

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.

Leon Glass
"Universal aspects of cardiac dynamics"

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.

Omar Hurricane
"How Ignition and Target Gain > 1 were achieved in inertial fusion"

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

Jürgen Kurths
"Climate Meets Complex Systems: Exploring Teleconnections in the Climate System via a Complex Network Approach"

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.

Ying-Cheng Lai
Arizona State University
"Predicting tipping points with machine learning"

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.

Maike Sonnewald
"Equations as emergent phenomena determined using machine learning: An ocean case study"

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.

Alexandra Volkening
"Quantifying models of biological pattern formation using topological techniques"

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.