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IP1

Modern Sensing and Physics Learning with Shallow Recurrent Decoders

Spatiotemporal modeling of real-world data poses a challenging problem due to inherent high-dimensionality, measurement noise, and expensive data collection procedures. We present **S**parse **I**dentification of **N**onlinear **Dy**namics with **SH**allow **RE**current **D**ecoder networks (SINDy-SHRED), a method to jointly solve the sensing and model identification problems with simple implementation, efficient computation, and robust performance. SINDy-SHRED uses Gated Recurrent Units (GRUs) to model the temporal sequence of sensor measurements along with a shallow decoder network to reconstruct the full spatiotemporal field from the latent state space using only a few available sensors. Our proposed algorithm introduces a SINDy-based regularization; beginning with an arbitrary latent state space, the dynamics of the latent space progressively converges to a SINDy-class functional, provided the projection remains within the set. Thus a dynamical system model is enforced in the latent space of the temporal sequence model. We conduct a systematic experimental study including synthetic PDE data, real-world sensor measurements for sea surface temperature, and direct video data. With no explicit encoder, SINDy-SHRED enables efficient training with minimal hyperparameter tuning and laptop-level computing; further, it demonstrates robust generalization in a variety of applications with minimal to no hyperparameter adjustments. Finally, the interpretable SINDy model of latent state dynamics enables accurate long-term video predictions, achieving state-of-the-art performance and outperforming all baseline methods considered, including Convolutional LSTM, PredRNN, ResNet, and SimVP.

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IP2

Hidden Networks: From Phase Reductions to Effective Network Interactions

From networks of interconnected neurons in the brain to coupled electrochemical reactions: The collective dynamics of interacting dynamical systems shape the function (or dysfunction) of many systems that are critical for our everyday lives. For coupled oscillatory processes, synchronization is a prime example of emergent collective dynamics. But how oscillators interact is not necessarily obvious from (physical) connections between the oscillators. Here we look at phase reductions as a way to uncover the hidden 'effective' network interactions for coupled oscillators dynamics. On the one hand, these give insight into when oscillators do and do not interact (despite a link). On the other hand, they elucidate when and how nonpairwise higher-order interactions shape synchronization phenomena in coupled oscillator networks.

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IP3

Data Driven Homological Approaches for Detecting Changes in Dynamical Systems

Persistent homology is a powerful tool for measuring shape and structure of data. In this talk, we explore methods for using this tool to detect homological changes in the underlying structure of dynamical systems. As a first step, we can simplify a vineyard of persistence diagrams into a CROCKER plot to provide visual representations of qualitative shifts in the structure of examples such as the Lorenz and Rossler systems. We will also construct a "homological bifurcation plot" to enable the identification of qualitative shifts, namely P-type (phenomenological) bifurcations, within stochastic dynamical systems, defined by structural changes in the probability density functions (PDF) of the state variables. The talk will explore the successful application of this method to stochastic oscillators, showcasing its effectiveness in algorithmically detecting P-bifurcations. This talk is based on joint work with many collaborators, including Firas Khasawneh, Ismail Gzel, Sunia Tanweer, Sarah Tymochko, Audun Myers, and David Muoz.

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IP4

Taming the Chaos of Computational Experiments

Have you ever had trouble understanding a computational experiment in a paper you were reading? How hard is it to revisit your own experiments from six months ago? In computational research, we can change our codes with just a few keystrokes and run them repeatedly with different random initializations and conditions, making it all too easy to lose track of precise experimental conditions. I'll discuss the principles of replicability, validation, reproducibility, and usability. This is pragmatic advice that will apply whether your experiments are using Python on a single CPU or a high-performance computation on a supercomputer. I'll cover the components of a computational experiment (code, data, scripts), the artifacts that can be used for validation, version control, replication, reproducibility, and usability. Ensuring that your experiments can be easily validated and your code easily used helps to broaden the impact of your work, making it easier for others to build on and extend. Moreover, creating expectations for computational validation in the field will strengthen the integrity of our work overall.

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IP5

A Journey Through Random Dynamical Systems and Multiplicative Ergodic Theory

Random dynamical systems serve as versatile mathematical models for analyzing systems influenced by external factors, such as seasonal variations and stochastic noise. Recent advancements in multiplicative ergodic theory have uncovered fundamental insights into transport phenomena within these systems, shedding light on their long-term behavior, mixing rates, coherent structures, and limit theorems. In this talk, we will journey through random dynamical systems and multiplicative ergodic theory, beginning with fundamental examples and addressing questions that arise from the study of oceanic and atmospheric flows.

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IP6

Agent-Based and Continuous Models of Locust Hopper Bands

An outstanding challenge in mathematical biology is using laboratory and/or field observations to tune a models functional form and parameter values. These problems lie at the intersection of dynamical systems and data science. In this talk I will discuss an ongoing project developing models of the Australian plague locust for which excellent field data is available. Under favorable environmental conditions flightless juveniles aggregate into coherent, aligned swarms referred to as hopper bands. We develop two models of hopper bands in tandem; an agent-based model that tracks the position of individuals and a continuum model describing locust density. By examining 4.4 million parameter combinations, we identify a set of parameters that reproduce field observations. I will then discuss ongoing efforts to improve these models. The first extends this work by modeling locust alignment via the Kuramoto model of oscillator synchronization. The second uses motion tracking of tens of thousands of locusts to shed light on how locust movement is influenced by social interactions. Finally, we reflect on how recent lab work is revolutionizing our understanding of locust visual perception and navigation, spawning a new class of agent-based models.

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IP7

Multiscale Models for Enhancing our Understanding of Tumor-Immune Dynamics and Combination Therapies

Increased understanding of molecular mechanisms that mediate the pathogenesis of cancers is leading to careful manipulation of these pathways and the development of new cell-specific approaches to cancer therapy. At the same time, advances in cancer immunotherapy have led to the reemergence of their clinical use and effectiveness. Using data-driven computational models is a powerful and practical way to optimize novel combinations of these two very different therapeutic options for clinical cancer treatment. This talk will highlight a suite of multiscale mathematical models designed to optimize targeted drug treatment strategies, alone and in combination with immunotherapy.

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IP8

Spectral Representations and Model Inference for Multiscale Biological Dynamics

Recent advances in experimental live-imaging techniques have enabled simultaneous measurements of physical and biological observables at unprecedented spatial and temporal resolutions. Prominent examples range from recordings of gene-expression dynamics in growing microbial communities to complex neuro-mechanical behaviors in higher organisms. One of the key challenges in mathematical biology in the coming years will be translating these high-dimensional multiscale data into low-dimensional dynamical models that can aid in classifying complex biological phenomena both within and across species and help reveal the underlying biophysical and biochemical mechanisms. In this talk, I will survey recent joint efforts with our experimental partner labs to understand the behavioral complexity of bacteria, algae, worms and other organisms by combing suitable spectral representations with different dynamical systems inference approaches.

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IP9

Relating the Future to the Past: The Non-autonomous Dynamics of Tipping Points

In many practical applications of dynamical systems, it is necessary to understand the behaviour of non-autonomous systems, i.e. dynamical systems where the rules of evolution that change with time. Although there are some deep results on properties of non-autonomous systems, it remains hard to make general statements about attracting behaviour without limiting to a specific class. Such a class consists of asymptotically autonomous systems, i.e. non-autonomous systems with autonomous past and future limits. Using the concept of pullback attractor, it is possible to understand many changes associated with tipping points in such systems. Some interesting consequences relate to the predictability of ensembles in cases where the limit attractors are chaotic and pullback attractors can support nonautonomous physical measure on the attractor. Example applications to problems in climate dynamics will be discussed.

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SP1

Jrgen Moser Lecture - Not Just Another Pretty Phase: The Use of Phase Models in Neuroscience and Biology

Phase models provide a useful formalism that can applied to study pattern formation across a wide range of oscillatory systems, including many that arise in biology. In this talk, I will first provide a survey of results that my collaborators and I have done on networks of coupled phase-models and their applications to several problems in biology. I will introduce the method of phase-reduction and then review the behavior of chains and arrays of nearest network oscillators and how this was used to explain certain phase patterns in the small intestine and lamprey. I will describe some work about spiral waves in nonlocally coupled oscillatory networks and how so-called spiral chimeras form. I will then turn to some results on the roles of noise in synchronization and phase-reduction and recent applications of Koopman theory that allow one to define phase in noisy systems. Finally, I will close with a few remarks on extended (higher order) phase reduction.

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CP1

Computational Topology Techniques for Detecting Exoplanet Signatures in Circumstellar Disks

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.

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CP1

Stoichiometrically-Informed Symbolic Regression for Extracting Chemical Reaction Mechanisms from Data

Determining chemical reaction mechanisms is foundational in many research areas such as catalysis, electrochemistry, combustion, and biochemistry that feature prominently in modern scientific and technological landscapes. In this talk, I will describe the development of a data-driven computational method to extract chemical reaction mechanisms from time-series chemical concentration data. The developed method is realized through the use of dynamic symbolic regressiona method in which a sparse analytical form for a dynamical system is discovered using data. We specifically develop a stoichiometrically-informed method to fit the rate constants in a reaction mechanism through differential optimization and couple that fitting method with an optimization approach that searches a symbolic space of possible reaction mechanisms to find the mechanism that best matches a time-series dataset of concentrations. Applying the method results in excellent agreement between true and predicted mechanisms over data from multiple linear and nonlinear reaction schemes, including when the method is applied to noisy data and to systems with fast/slow dynamics.

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CP1

Topological Approach for Data Assimilation (tada)

Many dynamical systems are difficult or impossible to model using high fidelity physics-based models. Consequently, researchers are relying more on data driven models to make predictions and forecasts. Based on limited training data, machine learning models often deviate from the true system states over time and need to be continually updated as new measurements are taken using data assimilation. Classical data assimilation algorithms typically require knowledge of the measurement noise statistics which may be unknown. In this paper, we introduce a new data assimilation algorithm with a foundation in topological data analysis. By leveraging the differentiability of functions of persistence, gradient descent optimization is used to minimize topological differences between measurements and forecast predictions by tuning data driven model coefficients without using noise information from the measurements. We describe the method and focus on its capabilities performance using the chaotic Lorenz system as an example.

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CP1

Uncovering Hidden Information from Oscillatory Time Series Data

Data-driven model identification techniques have transformed how scientists infer models of dynamical systems from data. Interpretable (white-box) machine learning methods like Sparse Identification of Dynamical Systems (SINDy) can generate symbolic differential equations that describe system dynamics. SINDy has been successfully applied to synthetic data across diverse fields, including engineering, physics, and biology. However, SINDy and similar methods have rarely succeeded in identifying interpretable models from real experimental datasets. Beyond data limitations like resolution, noise, and dimensionality, effective model discovery often requires understanding underlying phase space structures, which significantly impact results. Key information, such as nullcline forms and fixed-point positions, can be crucial for model identification. Previously, we showed that this hidden information can be uncovered by varying an offset in oscillatory data while applying SINDy. Although promising, this approach remains constrained by SINDys requirement for a term library and restriction to two dimensions. To overcome these limitations, we propose using a simple feed-forward neural network, trained on time series data, to directly reveal nullcline structures. Integrating this neural network insight

with SINDy allows us to leverage deep learning strengths while producing interpretable models in differential equation form, greatly enhancing model discovery from time series data.

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CP1

Exploring Network Dynamics Using Topological Data Analysis and the Equation-Free Method

In this work, we propose a method for analyzing the macroscopic dynamics of complex neuronal networks based on topological data analysis (TDA) and equation-free method (EFM). Initially, we project the dynamics of activated neurons in the network onto a circle S^1. Subsequently, a TDA filtration process is employed to determine the minimum radius R at which the $Betti_1$ number emerges. Using the equation-free framework, we construct a lifting method, which produces a microscopic network state based on the minimal filtration value R. Furthermore, within the framework of equation-free methods, we compute (numerically) an evolution law for the macroscopic network dynamics as a function of the topological property, e.g., as a function of the macroscopic radius R. Finally, we conduct a bifurcation and stability analysis of the macroscopic network dynamics.

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CP1

Learning to Learn Ecosystems from Limited Data - a Meta-Learning Approach

A fundamental challenge in developing data-driven approaches to ecological systems for tasks such as state estimation and prediction is the paucity of the observational or measurement data. For example, modern machine-learning techniques such as deep learning or reservoir computing typically require a large quantity of data. Leveraging synthetic data from paradigmatic nonlinear but non-ecological dynamical systems, we develop a meta-learning framework with time-delayed feedforward neural networks to predict the long-term behaviors of ecological systems as characterized by their attractors. We show that the framework is capable of accurately reconstructing the dynamical climate of the ecological system with limited data. Three benchmark population models in ecology, namely the Hastings-Powell model, a three-species food chain, and the Lotka-Volterra system, are used to demonstrate the performance of the meta-learning based prediction framework. In all cases, enhanced accuracy and robustness are achieved using five to seven times less training data as compared with the corresponding machine-learning method trained solely from the ecosystem data. A number of issues affecting the prediction performance are addressed.

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CP2

The Dynamics of Strategic Voting: Pathways to Consensus and Gridlock

The outcome of democratic elections rests on individuals' decision-making that is driven by their varying preferences and beliefs. Individuals may prefer consensus to gridlock, or gridlock to consensus, and information may be fractured via echo-chambers. To understand the role of these factors in whether or not elections reach consensus, we develop and explore a computational model of elections in which voters have varying party affiliations, preferences, beliefs, and voting strategies. Voters may change their voting strategies either by imitating others or reconsidering their strategy individually. Preferences are orderings of the following election outcome: a voter's party winning a super-majority, the opposing party winning such a majority, and gridlock. Voters beliefs are determined by their social networks, and thus beliefs are heterogeneous. We observe a "tipping point" phenomenon wherein the voters' initial strategies and randomness impact whether the minority party voters vote to create gridlock or consensus. A positive feedback loop secures such voters into one behaviour or the other. Furthermore, we find that consensus is promoted by an uneven distribution of party affiliation, and undermined when it is even.

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CP2

How Many Electoral Votes Will Texas Have in a Hundred Years?

Using Census Bureau data from 2005 through 2022, we develop and study a Markov model of migration among the states. It has a unique ergodic distribution. Given the state populations in 2023, the model forecasts the distribution of population among the states at any horizon. We use these predictions to determine the reapportionment of electoral votes. Taking advantage of the current historical anomaly of a highly polarized national electorate, we compute the Shapley-Shubik power indices for the eight jurisdictions that are pivotal in presidential elections. We analyze the stability of the Markov model and of inter-state migration patterns during the 17-year period of available data.

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CP2

Intelligent Intersection Management: Using AI to Replace 4-Way Stops with Real-Time Traffic Lights

Traditional 4-way stop signs contribute to higher collision rates due to driver confusion and non-compliance. This project proposes an AI-powered adaptive traffic signal system designed to replace 4-way stops, enhancing both safety and efficiency. The system integrates computer vision algorithms to detect vehicle types, speeds, and trajectories using real-time data from cameras and sensors installed at the intersection. A reinforcement learning model is then employed to predict traffic patterns and determine optimal signal timings. The AI system processes incoming data at the edge, using deep learning techniques for rapid decision-making with minimal latency. By dynamically adjusting red and green lights based on real-time conditions, the system reduces vehicle idle time and improves intersection throughput. Simulation tests in traffic management software demonstrate a reduction in delays and significant improvements in safety metrics, including a reduction in potential collision points. Furthermore, the model will incorporate a Vehicle-to-Everything (V2X) communication protocol for enhanced data sharing, supporting advanced predictive capabilities and preparing the system for future integration with autonomous vehicles. This AI-driven approach offers a scalable, adaptive solution that addresses the limitations of traditional stop-controlled intersections, providing a pathway toward safer and more efficient urban traffic management.

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CP3

Oscillatory and Chaotic Synchronization Behavior in Coupled Oscillator Systems with Higher Order Interactions, Community Structure, and Phase Lags

Despite the prevalence of higher order interactions, phase lags, and community structure in many complex systems, their combined effects in synchronization processes remain unexplored. In this study, we consider coupled oscillator systems with higher order interactions mediated via hyperedges of size 2 (links) and size 3 (triangles), two communities, and identical phase lags between every interacting oscillator group. For some phase lags values, the system exhibits oscillatory and chaotic synchronization behavior, which is not present only when higher order interactions and community structure, or community structure and identical phase lags, are included. Some phase lag values result in almost synchronized and almost in-phase or almost anti-phase communities. For other phase lag values, we observe synchronized states with in-phase, anti-phase and skew phase communities, and incoherent-synchronized states. These results are supported by analytical equations derived using the Ott-Antonsen ansatz and numerical simulations.

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CP3

Recurrent Neural Networks and Nonlinear Noise in Spatially-Extended Systems

Cortical responses are readily captured by circuit models where populations of excitatory and inhibitory neurons recurrently connect to one another. In their simplest form, these models typically include some coupling (usually random or otherwise space-free), some governing nonlinearity (usually sigmoidal), and some noise (usually white, and always outside the governing nonlinearity). We consider a spatially-extended model with deterministic spatially-modulated Gaussian coupling, a power-law nonlinearity, and spatio-temporally correlated noise acting as input driving the system. We argue that this model is a more physically plausible representation of the brain. This system has parameter regimes that form spatio-temporal patterns, and low dimensional dynamical chaos even in the purely deterministic, noiseless system. Using a novel treatment for nonlinear noise, we derive an analytical expression for the evolution equations which govern the means and correlations of the firing rates, anddevelop a dynamical mean-field theory in space and time. Numerical simulations confirm the validity of our methods, which can be extended to generically nonlinear noise, with few constraints. We further demonstrate that the correlation functions for the more traditional model with linear noise differ dramatically, and that the linear model is a poor substitute for including noise in the governing nonlinearity.

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CP3

Attention-Enhanced Reservoir Computing for Multi-Task Chaotic Time-Series Prediction with Attractor Switching

We present an Attention-Enhanced Reservoir Computer (AERC) as a universal dynamical system approximator, capable of predicting multiple chaotic attractors within a single framework. Classical reservoir computing approaches typically require task-specific training and face challenges when applied to diverse chaotic systems. Our AERC incorporates an attention mechanism into the output layer, enabling dynamic adaptation to distinct input features. Trained on five benchmark systems Lorenz, Rssler, Henon Map, Duffing Oscillator, and Mackey-Glass the AERC predicts these chaotic time series using a single set of weights. Results highlight improved prediction accuracy, valid prediction time, and enhanced spectral and histogram similarity compared to traditional models. A key result of the AERC is its ability to attractor switch by effectively separating chaotic systems in its embedding space. The attention mechanism dynamically adjusts the network's focus, enabling more robust long-term predictions and superior adaptability across various dynamical tasks. This makes AERC a powerful tool for chaotic time-series prediction.

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CP3

Optimizing Synchronization in Complex Networks: Efficient Coupling and Network Topology

Synchronization is a fundamental dynamical process that occurs spontaneously in both natural and technological networked systems. Though critical, the transient behavior leading to synchronization is often understudied. We introduce transverse reactivity to measure how perturbations grow or decay transiently in a network of coupled oscillators and propose an efficient coupling strategy that enhances synchronization across a wider range of coupling strengths. This approach is validated through simulations and experiments. We also examine how the network topology affects synchronization in terms of the newly introduced metric of network syncreactivity and analyze real-world networks. Our work advances theoretical insights and provides practical tools for optimizing synchronization in diverse applications.

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CP3

Asymmetric Limit Cycles Within Lorenz Chaos Drive Uphill Motion for An Active Particle

On applying a small bias force, non-equilibrium systems may respond in paradoxical ways, such as with negative mobility i.e. net motion in the direction opposite to applied force. Such behaviors have been extensively studied in passive non-equilibrium systems such as externally driven passive inertial particles. I will present our investigation of a minimal model of an active particle inspired from experiments with walking and superwalking droplets, whose equation of motion maps to the celebrated Lorenz system. By adding a small bias force to this Lorenz model, we uncover a dynamical mechanism for negative mobility rooted in asymmetric limit cycles within Lorenz chaos.

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CP4

A Comparative Exploration of Numerical Methods for Chemostat Models of Nutrient Recycling and Microbial Dormancy

This talk presents a comparison of several numerical methods for solving a simple model of nutrient recycling and dormancy in a chemostat. The study evaluates a range of techniques, including Eulers method, Runge-Kutta methods, implicit methods, nonstandard finite difference methods (NSFD). Each method is assessed based on criteria such as accuracy, stability, computational efficiency, and their ability to handle the specific characteristics of the chemostat model. Key findings indicate that while simpler methods like Eulers are easy to implement, they often lack the stability and accuracy needed for complex biological systems. In contrast, Runge-Kutta methods provide better precision but at a higher computational cost. NSFD methods emerge as particularly effective, preserving important properties of the dynamical system without any restriction on the time-step h, making them well-suited for modeling microbial dynamics. The implications of these findings underscore the importance of selecting the appropriate numerical method to accurately capture the dynamics of microbial populations in controlled environments, ultimately aiding in the effective management of these communities in various applications.

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CP4

The Spatiotemporal Dynamics of P. Mirabilis Swarm Cycling

Proteus mirabilis, a bacterium that naturally occurs in the gut, can traverse catheters and cause urinary tract infections. This migration, termed swarming, encompasses a dynamic developmental cycle in which populations oscillate between two primary states: (1) little-to-no movement with closely packed short cells and (2) micron-scale movement of short and dramatically elongated cells. As cells move, the colony migrates; its leading edge expands outward in a non-uniform way. We use computational geometry and computational topology to identify, characterize, and track the resulting structures in microscope photographs of *Proteus* colonies. Since these cells communicate by touching one another, adjacency is a particularly salient property. Density of the cells is also important, as is their alignment. Using these and other quantities, we can identify important features like the fractal dimension of the leading edge of a swarm, the local and global connectedness of the cells, and the alignment in different regions of the swarm. These results empower biologists with the ability to characterize mesoscale behaviors, such as disentangling the role of cell-cell communication in collective migration, which is a step towards a better understanding of how *P. mirabilis* causes disease.

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CP4

Spiral Waves Speed Up Cell Cycle Oscillations in the Frog Cytoplasm

Spiral waves are known to play important roles in biological systems, particularly in cardiac dynamics and cortical processes. Spiral waves in calcium activity have also been observed upon fertilization of the frog egg. The frog embryos also exhibit surface contraction waves - ripples in the cell cortex that precede cytokinesis. In vitro experiments using frog egg extracts suggest these ripples are caused by target pattern waves originating at the nucleus and spreading through the cytoplasm at a fixed speed to coordinate cell division. Existing mathematical models of the cell cycle oscillator in this system not only describe such target patterns, but also spiral waves. Here, we present the first observation of spiral waves in the cytoplasm of the frog Xenopus laevis using cell-free extracts made from frog eggs. We found that these spiral waves can decrease the period of cell cycle oscillations by up to two-fold. We then utilized two computational models - the FitzHugh-Nagumo model and a Cell Cycle model - to demonstrate that this period reduction is a general phenomenon of all relaxation-like oscillators primarily driven by time-scale separation.

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CP4

A Chemostat Model with Variable Dilution Rate Due to Biofilm Growth

In many real life applications, a continuous culture bioreactor may cease to function properly due to bioclogging which is typically caused by the microbial overgrowth. Many of models explicitly accounted for biofilm development inside the bioreactor. This is a problem that has been largely overlooked in the chemostat modeling despite the fact that many modern-day problems including chemostat involves bioclogging. In most of chemostat model, the physical volume of the biofilm is considered negligible when compared to the volume of the fluid. In this talk, we show the investigation of the theoretical consequences of removing such assumption. Specifically, we formulate a novel mathematical model of a chemostat where the increase of the biofilm volume occurs at the expense of the fluid volume of the bioreactor, and as a result the corresponding dilution rate increases reciprocally. We show that our model is well-posed and describes the bioreactor that can operate in three distinct types of dynamic regimes: the washout equilibrium, the coexistence equilibrium, or a transient towards the clogged state which is reached in finite time. We analyze the multiplicity and the stability of the corresponding equilibria. In particular, we delineate the parameter combinations for which the chemostat never clogs up and those for which it clogs up in finite time. We also derive criteria for microbial persistence and extinction.

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CP4

Interacting Hosts with Microbe Exchange: An Extension of Metacommunity Theory for Discrete Interactions

Microbiomes, which are collections of interacting microbes in a specific environment, often have substantial impact on the environmental patches or living hosts that they occupy. Differential equations are commonly used to model the local dynamics of microbiome systems, but it is also critical to consider non-local interactions. One way to model interactions across multiple scales—which can represent the local dynamics within an environment and the exchange of microbes between environments—is to employ metacommunity theory. Metacommunity models commonly assume continuous microbe exchange between the environments in which local microbiome dynamics occur. The exchange rates in these models are controlled by a single dispersal parameter. This framework is well-suited to abiotic environmental patches, but it fails to capture an important aspect of the microbiomes of living hosts. Specifically, living hosts generally do not interact continuously with each other; instead, they interact in discrete (and often short) time intervals. In this talk, we develop a modeling framework that successfully encodes such discrete interactions and uses two parameters to separately control the interaction frequency between hosts and the amount of exchange that occurs during each interaction. We analyze our model for several different regimes and demonstrate that both interaction parameters are necessary to understand the model's behavior.

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CP4

The Effect of Short Term Plasticity on the Synchrony and Rhythms of Hippocampal Interneurons

Neurons in hippocampus have been shown to coordinate their activity to form coherently firing networks at physiological frequencies. Interneurons (relatively few in num-

ber) are thought to provide a base non-plastic rhythm that can drive excitatory neurons (more numerous). Interneuron microcircuits in vitro, in vivo, and in silico have thus been extensively studied, with an emphasis on synchronous firing assemblies at gamma frequencies. More recently, the possibility of neuromodulation of interneurons in hippocampus has been experimentally studied, with evidence that PV+BCs do allow for neuromodulation through short term plasticity mechanisms at the presynaptic membrane. A model of the mechanism was parameterized from this data (leading to depression), which can be tuned to also apply to other types synapses (facilitating or mixed). In this talk we examine the effect of adding STP on interneuron microcircuits, both computationally and analytically. Small numbers of PV+BCs are studied, and their behavior is compared with large network simulations.

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CP5

Optimal Couplings of Undirected Graphs with Applications in Detecting Graph Isomorphisms

In this talk, we will introduce a new notion of optimal couplings for undirected graphs, which is based on constrained optimal transport between the simple random walks on the graphs. After giving the definition of optimal couplings for undirected graphs, we will state some of basic mathematical properties and then present results indicating that these optimal couplings can be used to detect and identify graph isomorphisms. We also present an algorithm for computation of optimal graph couplings, along with numerical experiments. This is a joint work with Bongsoo Yi, Kevin McGoff, and Andrew B. Nobel.

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CP5

An Approximate Master Equation Description of the Watts Threshold Model on Higher-Order Networks

Until recently, when modelling social spreading processes on networks, only pairwise interactions were considered. The most commonly used model for social spreading processes on networks is the Watts threshold model. In the Watts threshold model each node has an associated threshold and becomes active if its fraction of active neighbours meets its threshold. In reality, not all social interactions are pairwise. In this work, we use the extension of the Watts threshold model to higher-order networks of Chen et al. [L. Chen, Y. Zhu, Z. Ruan, M. Small, K. Christensen, R.-R. Liu, and F. Meng, A simple model of global cascades on random hypergraphs, arXiv preprint arXiv:2402.18850, (2024).], which is a discrete-time description and we study it in continuous time. Mean-field approximations are inadequate to accurately model these dynamics [J. P. Gleeson, Binary-state dynamics on complex networks: Pair approximation and beyond, Phys. Rev. X, 3 (2013), p. 021004.]. To ensure accuracy, we use approximate master equations (AMEs) to describe both the node and the group dynamics — this is unusual as most AME models of dynamics on higher-order networks use AMEs to track the group dynamics and a mean-field approximation for the node dynamics. Using two ansatzes, we reduce the high-dimensional system to three equations. This dimension reduction allows us to more easily explore the dynamics. Through linear stability analysis, we calculate a cascade condition among other quantities.

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CP5

Heteroclinic Cycles in Graphs

Networks of interacting nodes connected by edges arise in almost every branch of scientific enquiry. The connectivity structure of the network can force the existence of invariant subspaces, which would not arise in generic dynamical systems. These invariant subspaces can result in the appearance of robust heteroclinic cycles, which would otherwise be structurally unstable. Typically, the dynamics near a stable heteroclinic cycle is nonergodic, so time averages computed at any node do not converge. We report on different types of heteroclinic cycle in a variety of networks, including ring graphs, ring graphs with long-range connections, graphs with even less symmetry, and randomly generated graphs.

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CP5

Amazingly Fast Computations of Invariant Polydiagonal Subspaces Using Constraint Programming

Polydiagonal subspaces of $\mathbb{R}^n$ are defined by equations of the form $x_i = \pm x_j$. The M-invariant polydiagonal subspaces of $\mathbb{R}^n$ describe synchrony or anti-synchrony in a network of n nonlinear cells coupled with the adjacency matrix M. Computing all M-invariant polydiagonal subspaces is hard. We use constraint programming to do computations in minutes that took weeks with the previously state-of-the-art algorithm. We show results of the computation where M is the adjacency matrix of the 60-vertex

Buckyball graph.

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CP5

Exploring Multiple 1:1 Entrainment Regions in Biological Oscillators

Entrainment in biological oscillators is central to understanding dynamical systems and synchronization phenomena. In this study, we expand the scope of polyglot entrainment (multiple disconnected 1:1 regions in Arnold Tongue diagram) by exploring its manifestation in higher-dimensional systems (3D and 4D Hodgkin-Huxley models). Our findings indicate that polyglot entrainment which is previously observed only in two-dimensional slow-fast models is also present in the 3D HH model. We observed polyglot entrainment in the vicinity of HB point when the unforced system acts as a damped oscillator and the fixed point is located near a cubic-like manifold. We also examine the entrainment patterns within the Novak-Tyson circadian model and introduce the emergence of multiple disconnected 1:1 entrainment regions within Arnold onion diagrams, a departure from the single 1:1 region typically documented. Our findings suggest that in an unforced system behaving as a damped oscillator, multiple Arnold onions emerge near the Hopf bifurcation (HB) point, providing insights into the intricate mechanisms underlying circadian seasonality. This research advances the study of entrainment mechanisms across various types of oscillators contributing to the broader understanding of entrainment in nonlinear systems.

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CP6

Homoclinic Bifurcations in Discontinuous Planar Maps

The study of stable and unstable manifolds of saddle points, along with the homoclinic bifurcations resulting from their interactions, is a classic topic in nonlinear dynamics. The theory of these bifurcations was initially developed for smooth invertible maps and later expanded to include continuous piecewise smooth maps. Recently, however, there has been growing interest among researchers across various fields of nonlinear dynamics – both applied and theoretical – in discontinuous piecewise smooth maps. In smooth planar maps, the stable and unstable manifolds of saddles are generally smooth curves. In continuous piecewise smooth planar maps, however, the stable and invariant sets that play similar roles in dynamics may lose their smoothness. Consequently, homoclinic bifurcations in these maps may involve not only homoclinic tangencies but also homoclinic contacts at kink points. In contrast, the stable and unstable invariant sets of saddles in discontinuous piecewise smooth maps can themselves be discontinuous. We discuss some characteristic properties of these sets, particularly focusing on the homoclinic bifurcations in which these sets may be involved.

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CP6

A New Method for Analysing Torus Doubling Bifurcations

A torus in a continuous time dynamical system is represented by an invariant closed curve (ICC) on the Poincaré section. In a resonant (mode-locked) case, an ICC is the union of the stable cycle, the saddle cycle, and the unstable manifolds of the saddle. In a quasiperiodic case, the drift ring defines an ICC. It has been reported that such an ICC can undergo a doubling bifurcation, resulting in either two disjoint loops or a single closed curve of double length. Several approaches have been proposed to examine these bifurcations, typically specific to either resonant or quasiperiodic tori, without a unified approach for both cases. A theoretical method based on the topology (cylindrical or Möbius-strip-like) of the 2D center manifold has been developed for quasiperiodic tori, though its practical applicability remains limited. More practical approaches include the conjecture that, for resonant tori, the sign of the stable cycle's third eigenvalue determines the bifurcation type. Another method computes dominant Lyapunov bundles, defined for quasiperiodic tori as the set of Lyapunov vectors associated with the second-largest Lyapunov exponent. We indicate issues with these approaches and propose a new method that applies to both ergodic and resonant tori, based on the topological structure of the tangent space in the doubling direction. Additionally, for resonant tori, we show how the doubling type depends on whether the cycle period is odd or even.

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CP6

Characterizing Timbrical Properties of Different Bifurcations

Differential equations underlie the oscillatory solutions often observed in nature, which can represent animal vocalizations or "syllables". By examining bifurcations in dynamical systems, we understand how distinct sound qualities-or "timbres"-emerge. Each system produces distinct oscillatory properties, which we identify to form the

basis of timbre. Though defining timbre quantitatively is challenging, prior studies offer indices involving spectral features and envelope profiles. Here, we model amplitude via airflow dynamics, with oscillations shaped by specific biological mechanisms, and compute the indices associated with each one. Using those indices, we categorize vocal syllables created by well-known bifurcations into a "timbrical space" and compare them to real bird songs, which can give us identify the underlying mechanisms behind these sounds.

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CP6

Explicit Symmetry-Breaking of D_n-Equivariant Systems

Group theory has long been used to find and analyze the solutions to systems equivariant under a given representation Γ_1 of a symmetry group G. It can also be used when that symmetry is explicitly broken by an external factor belonging to a different representation Γ_2, such as a tilted Benard convection cell or a buckling beam with slightly non-square cross-section. We examine systems with dihedral symmetry D_n and use character theory to find all possible ways the symmetry can be broken explicitly. The resulting systems are (Γ_1, Γ_2)-coequivariant, and the normal forms can be found with Poincare series. We find solution branches and their stabilities for these systems.

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CP7

Exact Path Kernel Representations for Neural Networks

We explore the equivalence between neural networks and kernel methods by deriving the first exact representation of any finite-size parametric classification model trained with gradient descent as a kernel machine. We compare our exact representation to the well-known Neural Tangent Kernel (NTK) and discuss approximation error relative to the NTK and other non-exact path kernel formulations. We experimentally demonstrate that the kernel can be computed for realistic networks up to machine precision. We use this exact kernel to show that our theoretical contribution can provide useful insights into the predictions made by neural networks, particularly the way in which they generalize. In addition, we discuss a generalized exact path kernel gEPK which naturally decomposes model predictions into localized input gradients or parameter gradients. We will use this method to measure signal manifold dimension and inform theoretically principled methods for out-of-distribution detection on pre-trained models.

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CP7

Graph Reservoir Networks for Prediction of Spatiotemporal Systems

Reservoir computing is an example of computation-through-dynamics which uses untrained high-dimensional systems, combined with simple readout mechanisms, to model low-dimensional stimuli. However, reservoir networks have not been scaled to large scale systems, due to reservoir requirements such as low-rank inputs. Certain classes of scientific problems however, such as single and multivariate spatially embedded partial differential equations, follow uniform low-dynamics at multiple locations. Here, we investigate scaling by creating multiple small reservoirs which each respond to a spatial location or node. In such networks, we modulate the level of inductive bias of the network by imposing identical readouts at each node, or lateral connections between hidden units of adjacent nodes. Across three tasks, we find that imposing topological constraints of the stimuli increases performance compared to a single reservoir. Furthermore, lateral connections between adjacent reservoirs increase performance only when each reservoir has the same connectivity, rather than independent identically distributed connections. These results show how a combination of random reservoirs can be combined with task specific connectivity to allow the larger domain-informed network to utilize the useful properties of high-dimensional random sub-networks. Supported by the LDRD Program at Sania National Laboratories. Sandia is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

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CP7

Transfer Operator Analysis of Synchronized Oscillators That Solve Combinatorial Optimization Problems

The continuous dynamics of artificial neural networks can be used for solving discrete optimization problems, such as the Traveling Salesman Problem (TSP), which is given a set of cities or points in the plane, to find the shortest closed tour that visits every point. As shown by John Hopfield (Nobel Prize in Physics 2024) and David Tank in their 1985-1986 works, it is possible to encode all the details of the problem, basically the distances between pairs of points, in the weights of the network, and let the system converge towards a solution of the optimization problem. This strategy has been expanded recently with Ising and Boltzmann machines, implemented in electronic, magnetic, and optical systems. Now, the quality of the results obtained with these networks decreases as the sizes of the problems grow, and lags behind modern heuristics specifically designed for tackling hard problems. For these reasons, dynamical networks are not even considered for solving medium and large problems. Here in this contribution, with the aid of transfer operator methods, particularly the Perron-Frobenius operator, we study some of the causes that hinder the performance of the networks: intrinsic symmetries, multiple local optima, deformed basins of attraction, and transient chaos.

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CP7

Machine Learning of Group-Equivariant Interpretable Models

The homogeneity and isotropy of physical space requires mathematical models of natural phenomena to be equivariant with respect to symmetries including translations, rotations, and reflections. Unstructured data-driven model inference leads to an intractable optimization problem due to the high dimensionality of both the spatiotemporal data and the model search space. While popular approaches to dealing with symmetries such as data augmentation and symmetry-constrained neural network architectures may promote equivariance, they make only limited impact on tractability. On the other hand, symbolic algorithms have the potential to enforce strong inductive biases that not only incorporate known symmetries but also leverage symbolic representations that can parsimoniously parametrize a wide range of models. This talk introduces the first algorithm that fully encodes this knowledge, exploiting tensor representations of the symmetry group $O(n)$ to model systems via sets of partial differential or integro-differential equations represented as tensor networks. We design and implement formal languages representing models within these search spaces. The use of canonical forms and a satisfiability modulo theory solver allows for efficient automated synthesis, evaluation, and symbolic deduction of these models, with coefficients in each equation identified using a homogeneous variant of sparse regression. In conclusion, several applications to physical systems will be discussed.

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CP7

Data-driven Model Discovery with Kolmogorov-Arnold Networks

Data-driven model discovery of complex dynamical systems is typically done using sparse optimization, but it has a fundamental limitation: the assumption that the underlying governing equations contain only a small number of elementary mathematical functions. However, this sparsity condition fails in many cases, such as the Ikeda (optical-cavity) map in nonlinear dynamics and various ecosystems. To address this, we propose a general model-discovery framework based on the Kolmogorov-Arnold networks (KANs) that are not constrained by the sparsity condition. The KAN framework with a simple structure is capable of accurately capturing the complex behavior of such dynamical systems while offering greater interpretability compared to conventional neural networks. This interpretability provides insights into the dynamics generating the data, which are typically inaccessible in traditional black-box function approximation methods. Additionally, we demonstrate nonuniqueness in which a large number of approximate models of the system can be found that generate the same invariant set with the correct statistics, such as the Lyapunov exponents and KullbackLeibler divergence.

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CP7

Data-Driven Estimation of Principal Koopman Subspaces

Data-driven methods for identifying Koopman eigenfunctions and invariant subspaces have been intensively explored and successfully applied to dimension reduction modeling for unknown nonlinear dynamical systems. Among the Koopman eigenfunctions, those that fundamentally characterize a smooth linearizing conjugacy are referred to as principal Koopman eigenfunctions. While various approaches, such as dictionary learning, have been proposed to estimate Koopman invariant subspaces effectively, substantial computational resources are often spent on representing nonprincipal components. By reducing the effort devoted to nonprincipal components, the efficiency of representing the significant invariant subspaces could be improved. In this study, we propose a data-driven method to efficiently extract the principal Koopman invariant subspace, thereby improving the efficiency of Koopmanistic modeling.

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CP8

A Two-Downstream-Pipe Design to Stabilize Pressure Valves

Pressure relief valves are the last line of failure prevention in high pressure systems. A pre-compressed spring presses a valve disk against the valve seat. This way, the valve disk closes the protected system until the pressure level reaches the so-called set pressure, where the fluid forces exceed the spring force and the valve opens. Despite their simple structure, these valves can cause noise and dangerous pressure peaks in the protected system due to their intense vibrations. These vibrations are self-excited, influenced by the environment where the valve is installed. To understand this problem, a liquid service pressure relief valve is connected to a constantly charged vessel, while downstream pipes deliver the fluid to the atmospheric pressure. Previous work based on the single-pipe case showed that the length of the pipe appears as a transport time delay in the mathematical model, with a stabilizing effect. Stable and unstable behavior of the dynamics can alternate as the pipe length is increased up to an upper bound. Furthermore, a critical damping ratio can be associated with the so-called delay-independent stability however too large to realize in physical systems. In this presentation, we will present a model where two different size downstream pipes are utilized to create a two time-delay model with the opportunity to reveal stability properties that are impossible to achieve with a single time-delay model.

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CP8

Dynamical Compartments in Stirred Tank Reactors and Markov State Modelling for Mixing Quantification

In many chemical and biochemical reactors the optimization of mixing processes is a primary goal. We use transfer operator methods to extract coherent flow structures as almost invariant and/or coherent sets from simulated and experimental trajectory data of a stirred tank reactor. For the transfer operator approach, the domain is partitioned into small boxes. Transport between boxes is encoded in stochastic transition matrices and their dominant eigenvectors contain information on coherent behavior. The transfer operator framework allows us to set up a compartment model with the coherent sets and their surroundings serving as compartments. This Markov state model provides a simplified representation of the dominant dynamics of the system. There is little transport between compartments, while there can be high mixing within individual compartments. We analyze the mixing behavior, for example by computing expected residence times and mixing times.

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CP8

A Computational Model of Phonation-Induced Aerosolization

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.

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CP8

Transition to turbulence in the Stokes Boundary Layer: Edge States and Periodic Self-Sustained Process (PSSP)

The Stokes boundary layer is an oscillatory flow above an infinite plate subject to a sinusoidal motion. Beyond a critical Reynolds number of 2511, the laminar solution of the Stokes boundary layer is susceptible to linear instability. However, this instability is subcritical given that turbulence is observed for Reynolds numbers above approximately 700. The state space of a subcritical flow consists of two basins of attraction: that of the laminar flow and that of turbulence. A saddle point separates these basins, termed the edge state, and its codimension-one stable manifold termed the edge manifold, or simply edge. Edge states in the Stokes boundary layer are composed of vortical structures of the same nature as canonical shear flows, namely streaks, rolls and waves. For non-oscillating shear flows, these structures are known to coexist and mutually balance through a mechanism known as the Self-Sustained Process. However, in the Stokes boundary layer, these structures are inherently periodic and utilise the oscillating base flow in a novel way. Streaks are created by the action of the rolls through the lift-up mechanism. These structures rise up to align with the region where the perturbation velocity field can obtain energy from the background laminar flow (production window) to sustain them. This region migrates upwards at a non-dimensional velocity of $2\sqrt{\pi}$ up to a stagnation point, where they become unstable and loss coherence.

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CP8

Sheparding Ensembles in a Low Reynolds Number Flow Via the Perron-Frobenus Operator

The manipulations of a collection of particles in a low Reynolds number environment has several important applications. Micro rotors and micro pumps propelled by various mechanisms have been proposed as a useful means of transporting fluid particles. A method based on recent advances in dynamical systems is used to model and control the trasport of distributions of fluid particles using micro rotors in a Stokes flow. The distribution of fluid particles is described by a density function, and a finite dimensional approximation of the Liouville operator (the infinitesimal generator of the Perron-Frobenius operator) is developed to approximate the density transport problem. With this model the effect of combinations of different rotors is demonstrated and the controlled density transport problem is posed as an optimal control problem which is solved using differential dynamic programming. Using the Perron-Frobenius operator the numerically realized control input can be interpreted as producing coherent sets and transport structures in the flow.

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CP8

Linear Stability of Sub-Diffusive Plane Poiseuille Flow under the Magnetic Field

The linear stability and dynamics of viscoelastic, subdiffusive plane Poiseuille flow are investigated under the influence of a uniform magnetic field. The fractional upper convected Maxwell (FUCM) model captures viscoelastic phenomena. The neutral stability curves are analyzed for a range of Reynolds numbers, Weissenberg numbers, Hartmann numbers, and viscosity ratios. Present results revealed critical insights: shift in the most unstable mode with the change in the order of the fractional derivative. These present results not only advance our theoretical understanding of complex fluid dynamics but also present significant opportunities for real-world applications in diverse fields ranging from engineering and science.

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CP9

Trajectory-Based Stabilization of Periodic Orbits

We present a data-driven feedback control scheme, which stabilizes unstable periodic orbits of dynamical systems. Model equations of the underlying system are assumed to be unavailable. Our approach relies only on previously measured input-state time series of a Poincare map of the system. For a successful implementation of feedback control in experimental systems one typically has to choose adequate control gains. The presented scheme computes stabilizing control gains by solving an optimization problem. No explicit model is identified and the control gains are computed directly from the measured time series. As a demonstration, we apply the scheme to a control-based continuation problem.

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CP9

Observer-Based Physics-Informed Neural Network Design for Fault Estimation

Generally, faults are unknown, and there are three major types: sensor faults, actuator faults, and component faults, which are significant factors affecting most dynamical systems. Therefore, it is essential to detect and estimate the impact of these faults to improve system performance. Additionally, these faults are highly complex and nonlinear in nature, and sensor and actuator faults can simultaneously affect the system, creating a worst-case scenario. To address this issue, this work presents an integrated observer-based, physics-informed neural network design to estimate sensor and actuator faults simultaneously. Specifically, the state vectors of the dynamical system, along with sensor and actuator faults, are estimated using a neural network model. This neural network model is trained using physical information on sensor and actuator faults, estimated via observer techniques. Furthermore, existence and stability conditions are established using the well-known Lyapunov stability theory. Finally, the theoretical results are validated through numerical simulations.

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CP9

Energy-Efficient Stochastic Control Design for Neural Oscillator Networks

We present a computational framework for optimal control of neural oscillator networks that explicitly accounts for stochastic dynamics. Our approach centers on solving the stochastic Hamilton-Jacobi-Bellman (HJB) equation through advanced level set methods, particularly focusing on the energy-efficiency aspects of control implementation. By incorporating system noise into the optimal control formulation, we demonstrate how stochastic effects can be leveraged to achieve control objectives with reduced energy expenditure. The numerical solutions reveal that accounting for noise in the control design leads to more efficient stimulation patterns compared to deterministic approaches. Our results show robust performance across different network configurations, with particular effectiveness in sparsely connected networks. The framework provides insights into the relationship between noise intensity, optimal control policy, and phase synchronization, offering a foundation for developing energy-aware control strategies in neural systems. The method demonstrates particular efficiency in desynchronizing coupled oscillators while minimizing the control energy cost function, suggesting optimal strategies for stochastic phase reduction approaches.

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CP9

Sampled Data Control of Delayed Cutting Processes

The vibrations in machining processes like turning or milling are described by delayed differential equations. The time delay appears due to the regenerative effect: the cutting forces are dependent on both the current displacement of the tool and workpiece as well as their displacement during the previous cut. These complex dynamics can lead to harmful chatter vibrations which limit productivity and part quality. There are many approaches to reduce chatter: using specially designed tools, adaptive feed rate control or using an active support [J. Munoa, et al., Chatter suppression techniques in metal cutting, 2016]. Many of these methods rely on active control loops usually implemented using digital controllers, which means sampled data is used. The interaction of the constant delay existing in the machining operation and the sampling delay originated in the control loop present an intricate dynamical problem. Our work is focused on the stability analysis of sampled data control of delayed oscillators. We have found analytical methods, which produce closed form characteristic equations for these problems that can be used to find the stability boundaries analytically or semi-analytically. These results not only provide insight into the structure of these stability charts and the effectiveness of the chatter suppression techniques, but also serve as a trial problem for testing numerical methods [T. Insperger, G. Stepan: Semi-Discretization for Time-Delay Systems, 2011].

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CP9

Nonlinear Dynamics of Electric Unicycles: Balacing Lateral and Longitudinal Actions

Electric unicycles are becoming a popular transportation method in urban environments. The unicycles high levels of agility and maneuverability attract researchers to analyze their dynamics and apply this knowledge in the development of autonomous unicycles. In case of straight rolling, the lateral and longitudinal dynamics may be decomposed. However, to exploit the capabilities of the unicycle, the full nonlinear nonholonomic dynamical model has to be compiled. Our unicycle model extends the rolling wheel with actuators for both acceleration/breaking and steering. Compared to the rolling wheel, the closed form dynamical analysis of the unicycle yields new types of equilibria, such as tilted spinning, non-tilted turning, and turning-rolling steady states. The latter has two types: (i) when the center mass of the rider is pushed outside the wheel center which is utilized to perform sharp turns at low speed; (ii) when the center mass of the rider is inside the wheel center which is utilized to perform slanted turns at high speed. This duality is related to the presence of a critical speed above which the unicycle self-stabilizes in lateral direction. The model is transformed to path reference frame for control design. The designed path-following controller is capable to carry out maneuvers, such as lane changes and 90 degree turns. The developed nonlinear control strategies serve as a basis for designing ride-assist features.

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CP9

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

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.

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CP10
Periodic Inhomogeneities in Multi-Dimensional Pattern Forming Systems

The forms of explicit symmetry-breaking factors and their effects on previously symmetric pattern forming systems can be found with the use of Poincare series and equivariant bifurcation theory. We find the general forms of such factors for the case of periodic imhomogeneities in multi-dimensional pattern forming systems, such as might arise when a second Turing instability takes place in the presence of a pattern formed by a previous Turing instability.

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CP10
Think Global, Act Local: Fully Localised 2D Patterns Induced by Spatial Heterogeneities

There has been recent interest in the emergence of coherent structures in PDEs with spatial heterogeneities, both as a mathematical curiosity and as a relevant model for physical phenomena. In this talk I will discuss how the inclusion of a compact region of spatial heterogeneity can result in the emergence of fully localised 2D patterns. Here, the added heterogeneity allows us to prove the existence of these patterns, which remains an open problem in spatially homogeneous models. In particular, we obtain local and global bifurcation results for fully localised patterns both with and without radial or dihedral symmetry.This work is in collaboration with David J.B. Lloyd and Matthew R. Turner (both University of Surrey).

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CP10
Pattern Formation in Reaction-Diffusion Systems with Spatially Periodic Coefficients

We are interested in the formation of patterns that arise as solutions to nonlinear partial differential equations with spatially varying coefficients. We focus on one-dimensional patterns that are described by the evolution of modulated periodic orbits that bifurcate from a background state in the presence of a spatially varying heterogeneity. These nonlinear PDEs with spatially varying coefficients emerge from application based models, such as ecology models, where the spatially varying coefficients represent a spatially varying terrain. In this case, the corresponding solutions can be interpreted as vegetation patches adjusting to the periodic domain, hence forming patterns on patterns. During this talk, we'll showcase along various examples of PDEs with spatially periodic coefficients, such as Klausmeier and Swift-Hohenberg, how Bloch analysis can be used to derive the corresponding modulation equation. An additional challenge is caused by resonance phenomena, hence we have to distinguish between resonant and non-resonant cases, based on the wavenumber of the forcing.

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CP10
Orbital Stability of Periodic Plane Waves in the Klein-Gordon Equation Against Localized Perturbations

Nonlinear stability for spatially periodic waves in dispersive systems has so far been obtained against co-periodic or subharmonic perturbations by leveraging the Hamiltonian structure or other conserved quantities. Yet, nonlinear stability against localized perturbations is largely unexplored. Since the perturbed wave is neither periodic nor localized in this case, the usual conservation laws are unavailable, thus obstructing a standard nonlinear stability argument. In this talk, I present nonlinear orbital stability results for plane waves in the one-dimensional Klein-Gordon equation against L^2-localized perturbations. Plane waves are periodic traveling waves of the form $u(x,t) = \rho e^{i(kx+\mu t)}$ with amplitude $\rho > 0$, wavenumber $k \in \mathbb{R} \setminus \{0\}$ and frequency $\mu \in \mathbb{R}$. We establish that the perturbed solution is at any point in time locally uniformly close to a translate of the original plane wave. Our analysis yields nonlinear modulational stability of the plane waves, where we allow for nonlocalized initial phase off-sets. This is joint work with Emile Bukieda and Louis Garnaux.

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CP11
Bayesian Reconstruction of Intake Manifold Dynamics with Parameter Calibration

In internal combustion engines, access to calibrated physical models of subsystems is crucial for predicting emissions. Specifically, characterizing the intake manifold (IM) temperature and pressure can helps predict the behavior of the cylinder contents, which largely impact the performance. Rather than working with a complex and multidimensional model, we employ a mean value model (MVM) to accurately capture the IM states. However, in situations where heat transfer affects cannot be ignored, the standard MVM contains unknown physical parameters representing various material properties. This also causes the dynamics to appear in a nonlinear way. When coupled with noisy measurements, a Bayesian approach is needed to identify both the IM states and physical parameters. One would typically apply a variant of the Kalman filter suitable for nonlinear dynamics. For real engine datasets this is computationally unfeasible, as there are often hundreds of thousands of data points. We demonstrate how information field theory (IFT) can be applied to solve this filtering and calibration problem. We demonstrate the method across different datasets with varying degrees of fidelity collected from real engines. By encoding the MVM into a physics-informed prior, the predictions remain robust with low-fidelity data. The IFT posterior also quantifies the uncertainty about the IM material properties.

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CP11

Kinetically Consistent Coarse Graining Using Kernel-Based Extended Dynamic Mode Decomposition

Accurately detecting the coarse-grained coordinates is an essential task in the model discovery of complex systems, such as molecular dynamics. In this work, we show how kernel-based approximation to the Koopman generator the kgEDMD algorithm can be used to identify implied timescales and meta stable sets in stochastic dynamical systems, and to learn a coarse-grained dynamics on reduced variables, which retains the essential kinetic properties of the full model. The centerpiece of this study is a learning method to identify a state-dependent effective diffusion in coarse-grained space by leveraging the kgEMD model for the Koopman generator. By combining this method with force matching, a stochastic differential equation governing the effective dynamics can be inferred. Using a two-dimensional model system and molecular dynamics simulation data of alanine dipeptide, we demonstrate that the proposed method successfully and robustly recovers the essential thermodynamic and kinetic properties of the full model.

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CP11

Data-Driven Model Reduction Via Non-Intrusive Optimization of Projection Operators and Reduced-Order Dynamics

Computing low-order models using non-intrusive methods is attractive for systems that are simulated using black-box solvers. However, obtaining accurate data-driven models can be challenging, especially if the underlying systems exhibit large-amplitude transient growth. Although these systems may evolve near a low-dimensional subspace that can be easily identified using standard techniques, computing accurate models often requires projecting the state onto this subspace via a non-orthogonal projection. While appropriate projection operators can be computed using intrusive techniques that leverage the form of the underlying governing equations, purely data-driven methods tend to achieve dimensionality reduction via orthogonal projections, and this can lead to inaccurate models. We address this issue by introducing a non-intrusive framework designed to simultaneously identify oblique projection operators and reduced-order dynamics. In particular, given training trajectories and assuming reduced-order dynamics of polynomial form, we fit a reduced-order model by solving an optimization problem over the product manifold of a Grassmann manifold, a Stiefel manifold, and several linear spaces. Furthermore, we show that the gradient of the cost function with respect to the optimization parameters can be conveniently written in closed form, so that there is no need for automatic differentiation. We compare our formulation with state-of-the-art methods on several examples.

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CP12

Dynamic PageRank for Discrete and Continuous Time

The PageRank algorithm, central to Googles success in web search, has transformed how relevance is measured in complex networks by randomly surfing the link structure with random jumps. In this talk, we explore dynamic PageRank by making the adjacency matrix, damping factor, and personalization vector dependent on time. Both continuous and discrete time intervals are considered, and it is shown that the PageRank of a continuous temporal network can be nicely estimated by the PageRanks of the discrete temporal networks. Additionally, precise boundaries are given for the estimated influence of the personalization vector on the ranking of a particular node. This work has been partially supported by INCIBE/URJC Agreement M3386/2024/0031/001 within the framework of the Recovery, Transformation and Resilience Plan funds of the European Union (Next Generation EU).

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CP12

Critical Threshold for Synchronizability of High-Dimensional Kuramoto Oscillators under Higher-Order Interactions

Collective synchronization of the Kuramoto model has been extensively studied in diverse scientific disciplines, and since then, it has been generalized in various perspectives. As the Kuramoto model itself is defined on the unit circle as a one-dimensional object, it however would not be suitable to model high-dimensional behaviors appropriately. Moreover, another limitation is that it is restricted to two-body interactions. In this work, we focus on the high-dimensional Kuramoto model particularly together with three-body interactions. For this model, we find a critical threshold for complete synchronizability in terms of interaction strengths. Precisely, by denoting κ_1 and κ_2 for two- and three-body interaction strengths, respectively, we show that if $\kappa_1 + \kappa_2 > 0$, then complete synchronization can emerge, whereas if $\kappa_1+\kappa_2<0$, then complete synchronization cannot occur. For the critical case $\kappa_1+\kappa_2=0$, we show that the emergence of complete synchronization crucially depends on the sign of κ_1 and particularly that critical slowing down is observed at critical transition. Our theoretical results are supplemented by numerical experiments which also provide qualitative insight not captured in the theoretical analysis.

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CP12

Inferring Networks from Oscillatory Signals in Synchronous Systems

Synchronization is a ubiquitous phenomenon in nature, often described mathematically by means of coupled oscillators. The interaction network strongly influences the synchronization state and plays a crucial role in controlling the dynamics. To understand and control synchronization dynamics in the real world, it is essential to identify the network from observed data. While previous studies have developed methods for inferring networks in asynchronous systems, inferring the network of well-synchronized oscillators remains challenging. In this study, we present a method for non-invasively inferring the network of synchronized oscillators. This method exploits the circle map, which describes phase changes within an oscillatory cycle. Although our method discards a substantial portion of the data used for inference, its effectiveness is supported by phase reduction theory for weakly coupled oscillators. We validate the proposed method using simulated data from limit-cycle oscillators. This study marks an important step towards understanding synchronization in real-world systems from a network perspective.

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CP12

Effect of Frequency Heterogeneity on Chimera States in Nonlocally Coupled Oscillators

Chimera states in systems of nonlocally coupled oscillators, namely, self-organized coexistence of coherent and incoherent oscillator populations, have attracted attention [1-3]. In this study, we consider the effect of spatial frequency heterogeneity of the oscillators on the chimera states and show that it leads to spatial locking of the chimera states, that is, regions with relatively low-frequency oscillators attract the coherent population. Based on a modified self-consistency theory, we numerically reproduce the chimera states in the continuum limit under the frequency heterogeneity, and explain the mechanism leading to the spatial locking of the chimera states using a variational argument.
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CP12

Desynchronization Facilitates Energy-Optimal Phase Resetting of Coupled Oscillators

Phase resetting, involving shifting the timing of oscillations by a prespecified amount, is a fundamental control problem arising in the investigation of oscillatory dynamical systems. This problem has practical relevance in the development jet-lag mitigation strategies for reentraining one's circadian oscillations to a new light-dark cycle after rapid travel through multiple time zones. In this presentation, I will discuss recent results highlighting relationships between phase resetting and desynchronization in populations of coupled oscillators. When viewing from the perspective of an optimal control problem, two solution archetypes emerge: weak resetting which does not influence interoscillator synchrony and strong resetting whereby the network is first desynchronized before resynchronizing with the correct phase. Analytical expressions for the energy expenditure associated with these solutions yield general conditions for which desynchronization is expected during the course phase resetting. In particular, strong phase resetting is more efficient than weak resetting when the following conditions are met: 1) the population oscillation's relaxation rate to its limit cycle is sufficiently slow relative to the natural frequency and 2) the required phase shifts are sufficiently large.

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CP13

Numerical Analysis of Hybrid Timescale Consumer-Resource Interactions

Many species have a consumer-resource relationship that could involve exploitation, competition, facilitation, or a mix of many interactions. Though these processes can be modeled using continuous or discrete methods, relying solely on either method may not fully capture the dynamics of these interactions. Hence, this work combines continuous and discrete approaches in two and three-species model formulations that embody linear versus saturating responses to describe consumer-resource interplay. One of these formulations includes modeling facilitation and competition in drug-sensitive and drug-resistant tumor cells. For models with this hybrid nature, it is vital to understand the population dynamics as parameters vary. However, identifying and understanding the behaviors possible requires careful analysis and computations. In this study, we use a numerical approach to explore the possible behaviors these models can exhibit for our parameter space. These are accomplished by testing the models over multiple parameter sets and initial conditions using Latin Hypercube Sampling. We identify parameters and initial conditions that produce the persistence of the species in each model, compare the behavior in different regions to existing bifurcation curves, obtain a better understanding of parameter regions, and discuss the biological meaning behind these model formulations.

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CP13

A Minimal Mathematical Model for the Dynamics of Group Conversations

Conversation, as a fundamental aspect of language, profoundly shapes social interactions and relationships. Through conversations, individuals build and sustain social bonds, with particular patterns of interaction often underlying collaborative relationships. In this work, we develop and analyze a model of group conversation dynamics that predicts speaking times and interaction patterns among participants. The model is originally formulated as a piecewise linear dynamical system but simplifies to an iterated map. It assumes each participant has an internal "desire to speak" when listening and that this desire can change discontinuously only during speaker changes. Applying our model to a series of recorded group conversations around scientific themes, we find that predictions perform surprisingly well despite the model's simplicity.

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CP13

Prescribed Group Discussions at Conferences Have a Lasting Impact on Patterns of Collaboration Years Later

Do conferences promote novel scientific collaboration? Specifically, can prescribed discussions during the conference help ignite innovative research programs between scientists unlikely to collaborate in the absence of the conference interactions? We address this question using detailed multi-year observational data collected at four Scialog conferences. We focus on the effect of two prescribed interaction typessmall group meetings between previously unacquainted scientists and large group discussions among researchers with shared scientific interests. We demonstrate that small group assignments largely dictate team formation during the first year of Scialog conferences. This is consistent with published findings and is well-explained by an ODE model. In addition, we show that this effect persists but decays in magnitude during the follow-up years. Finally, we present the first evidence that large group discussions have a lasting impact on patterns of scientific collaboration. For instance, we show that pairs of researchers who shared a discussion group are more likely to coauthor papers years after the conference.

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CP13

Consensus Modeling for ML, Human-AI Teams, and Multiway Coordination

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.

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CP14

Leveraging Differentiation of Persistence Diagrams for Biological Parameter Space Optimization

Persistent homology, the flagship tool from Topological Data Analysis (TDA), has been successfully utilized in many different domains despite the absence of a differentiation framework. Only recently, a differential calculus has been defined on the space of persistence diagrams, thus unlocking new possibilities for combining persistence with powerful solvers and optimizers. This work explores harnessing persistence differentiation for navigating the parameter space of dynamical systems to achieve desired response characteristics based on the topological features of the signal. This optimization problem results in the formation of a path in the system parameter space to optimally lead the system to a response with the specified properties. We use these tools to study biological oscillator systems to develop loss functions that promote system parameters that lead to limit cycle behavior, which can provide valu-

able biological insight for researchers.

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CP14

Towards Foundation Models for Advanced Plant Phenotyping and Modeling

The development of sustainable perennial crops capable of thriving in suboptimal environments is critical for converting biomass into advanced bioproducts (e.g., sustainable aviation fuel). Achieving these goals requires linking gene functions to observable traits through high-throughput measurements. However, scarce high-quality datasets and labor-intensive phenotyping remain significant challenges. Deep learning offers fast and accurate image-based phenotyping but is bottlenecked by the availability of annotated training data. Here we discuss segmentation methods focused on enhancing predictive accuracy while minimizing reliance on extensive annotations and ensuring biologically realistic morphological features. Extracted traits (e.g., plant area, perimeter) are validated against empirical measurements and used in subsequent genome-wide association studies (GWAS). We further demonstrate how typical narrow-AI (models trained on specific datasets for a specific purpose) struggle to generalize outside of their training distribution (adapting to new species, plant characteristics, etc.), and how emerging vision-language foundation models perform zero-shot segmentation without the need to fine-tune or train new models from scratch. The resulting time series plant phenotypes have the potential to enable dynamical systems modeling of growth and physiology, supporting the development of mechanistic models that simulate plant response and resilience over time.

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CP14

Modeling Adoptive Cell Therapy in Bladder Cancer Using Physics-Informed Neural Network with Biology Constraints

Intravesical adoptive cell therapy (ACT) with tumor-infiltrating lymphocytes (TIL) holds promise for durable responses in bladder cancer by administering TILs locally, thus maximizing T cells numbers in the tumor area. However, T cells in the bladder encounter an immunosuppressive population of stromal cells such as myeloid-derived suppressor cells (MDSCs), that can weaken T cell efficacy. Intravesical delivery of gemcitabine acts as a local lymphodepletion agent, which preconditions the bladder microenvironment for the infused T cells. To understand the underlying biological mechanisms and optimize T cell response, we employ the physics-informed neural network (PINN), with an adaptive learning rate when the PINN loss stagnates. Using a pre-clinical murine model, bladder tumor growth was measured via ultrasound, and mice were separated into untreated, gemcitabine only (GEM), OT-I only (OT-I), and combination (GEM + OT-I) groups. An ordinary differential equation (ODE) model of tumor cells, T cells, and MDSCs interactions under the 4 different treatments is used to study the changing interactions over time between various compartments. Biological constraints are enforced on the compartments using a one-time-point histology data. We learn different scenarios of time-varying recruitment rate of MDSCs and describe its underlying implication for the biological mechanism of T cell efficacy.

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CP14

Data-Driven Reduced Order Modeling Techniques for Neuronal Networks of Subnetworks

Phase-amplitude reduction is an extension of phase reduction that uses isostable coordinates to account for deviations from a stable limit cycle. One of the important extensions of reduced-order modeling techniques is the application of these techniques to data-driven models. In this work, we draw a parallel between known phase-amplitude reduction techniques and a data driven application. The data driven model we consider is a heterogeneous network of neuronal subnetworks with all-to-all coupling and a complicated coupling structure. Since this is a data driven model, each neurons internal dynamics cannot be isolated from its coupling dynamics; this makes simple phase reduction, which analyzes the system using only a single stable limit cycle, inadequate. Phase-amplitude reduction can adequately characterize deviations from the stable limit cycle using associated isostable coordinates. To determine the terms of the associated phase-amplitude reduction, we define a single state (the average voltage) that is used to represent each subnetwork. Each subnetworks average voltage has an associated limit cycle, with deviations from that limit cycle caused by both heterogeneity in the network and coupling. Using measurements from associated isochron crossings, we derive terms for the reduced order model using a least-squares fit with phase-difference coupling. To verify the results further, we also derive a data-driven phase response curve and use it to model an applied input.

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CP15

A Dynamical Model of the Sheep-Dog Herding Problem

Efficient herding of multiple sheep by experienced sheepdogs with little to no human interference has led to significant interest in studying their interaction dynamics. In this work this naturally occurring dynamical game is modelled as a planar herding problem, where a single superior pursuer attempts to herd a flock of non-cooperative, inferior evaders around a predefined target point. An inverse square law of repulsion is assumed between the pursuer and each evader. A class of constant-angular-velocity spiral pursuer trajectories, centred around the target point, is proposed. The radial velocities of the pursuers are adjusted dynamically according to a feedback law which depends on the position of the furthest evader. It is shown that, under suitable conditions involving the respective initial conditions, magnitude of the pursuer angular velocity, and the strength of pursuer-evader repulsion, the evaders get herded into an arbitrarily small limit cycle around the target point. Meanwhile, the pursuer also converges onto a circular trajectory around the target. The conditions for the stability of this limit cycle, as well as the radius of the limiting herd, are derived. Maximal ellipsoidal estimates of the region of attraction for this stable limit cycle are calculated numerically. It is observed that the size of the region of attraction depends on the angular velocity, the pursuer's initial radius, and the initial positions of the evaders.

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CP15

Theoretical Framework for Acoustic Communication Between Mosquitoes

Distortion products are tones produced through the nonlinear response of a system simultaneously detecting two or more frequencies. These combination tones are ubiquitous to vertebrate auditory systems and are generally regarded as a byproduct of nonlinear signal amplification. It has previously been shown that several species of infectious-disease-carrying mosquitoes utilize these distortion products for detecting and locating potential mates. Using a generic numerical model for acoustic signal detection, we demonstrate that tuning a detector to these distortion products yields immense benefits on the frequency selectivity of the system. This enhanced frequency selectivity could be essential for male mosquitoes to be able to identify and pursue a particular female within a noisy swarm environment.

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CP15

Data-Driven Modeling of Honeybee Communication During Aggregation and Food Exchange

Honeybees exhibit remarkable division of labor in managing a diverse range of tasks within the hive, including the exchange of food via a process known as trophallaxis. The associated communication mechanisms remain largely unexplored. We leverage data obtained from laboratory experiments to study the communication mechanisms involved in food distribution via trophallaxis. We employ computer-vision techniques and convolutional neural networks to detect bee behaviors in video images, such as scenting (vigorous wing-flapping to propagate pheromones directionally), allowing us to study their impact on aggregations and food distribution. We demonstrate that honeybees can communicate through scenting, form aggregations around food sources, and distribute the food. This is an example of extended classical stigmergy: Instead of depositing static information in the environment, individual bees can communicate by perceiving and manipulating the physical fields of chemical concentration and airflow. Using insights from these experiments, we build an agent-based model that incorporates directional scenting and use it to study aggregation patterns and food distribution times. We find that directional scenting makes the model a better match to experimental observations and speeds food homogenization. Overall, these findings demonstrate that scenting is an effective communication mechanism for locating moving targets (i.e., food sources) for food exchange in honeybee groups.

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CP15

Self-Organization of Locomotion Through Autonomous Parameter Tuning

A model of peristaltic locomotion with autonomous parameter tuning is presented. The model autonomously generates a stable elongation-contraction wave while dynamically identifying the appropriate anchor timing. The parameter tuning system is conceptualized as a distributed system, enabling effective adaptation to environmental changes.

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CP15

Data-Driven Macroscopic Modeling of Crowd Dynamics Using Machine Learning: A Conservative Approach.

The emergent behavior of complex systems, such as crowd dynamics, is often analyzed at a macroscopic level using partial differential equations (PDEs). However, solving these PDEs can be computationally expensive, and predictions may diverge from real-world phenomena. This highlights the need for alternative approaches that effectively simulate complex systems without the limitations of traditional PDE models. To address this, we introduce a machine learning framework to approximate the solutions of hyperbolic-type PDEs in crowd dynamics. We generate position and velocity trajectories for N pedestrians in a 2D space using the social force model, a widely used agent-based method in crowd simulations. From these trajectories, we estimate macroscopic variables like density and momentum using kernel density estimation, linking individual dynamics with aggregate behavior. This data trains a neural network to predict macroscopic quantities over time in two stages: a sequential phase followed by refinement using a recurrent neural network to capture temporal dependencies, improve accuracy and reduce error accumulation in long term predictions. A conservation term is added to the loss function to enforce density conservation. We validate the methodology by testing it on initial conditions outside the training and test datasets, demonstrating robustness and generalization.

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CP15

Rationalizing Altruistic Behavior Via Bio-Inspired Models for Animal Huddling

Many species of animals have evolved to have behavior that seems altruistic to humans, such as huddling for warmth in cold temperatures. Furthermore, several species that huddle, including penguins and rodent pups, have been observed to continuously cycle who is in the middle so that everyone equally benefits. We showcase a dynamical system model for this behavior in which temperature is exchanged between animals and is coupled with a model for their movement. We also consider how to evaluate equity along with metrics that may be beneficial to the species in such models, in order to explain why animals may have evolved to have this behavior.

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CP16

An Exact Sir Series Solution and An Exploration of the Related Parameter Space

A convergent power series solution is obtained for the SIR epidemiology model, using an asymptotically motivated gauge function. For certain choices of model parameter values, the series converges over the full physical domain (i.e., for all positive time).

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CP16

Modeling, Inference, and Prediction in Mobility-Based Compartmental Models for Epidemiology

It is well known that many compartmental models have a tendency of over-estimate the size of a pandemic. To partially address this issue, we introduce mobility into the standard compartment model. At the beginning of a pandemic, individuals with higher mobility are more likely to be infected, which leads to an overestimate of the eventual pandemic size. Our results suggest that our mobility-based model predicts a smaller final pandemic size compared to the classical model, given the same number of basic reproduction number. Additionally, we will demonstrate how to use deep learning tools to estimate the mobility distribution in a community. Further connections with opinion dynamics will also be discussed.

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CP16

Benefits of Early Measles Vaccination: A Compartmental Modelling Study

Measles, a highly contagious viral disease, remains a significant public health challenge worldwide despite the availability of an effective vaccine. Traditionally, WHO recommends the first dose of the measles vaccine to be administered at 9 months of age, based on the risk of maternal antibody interference and the timing of infant immune system maturity. However, infants younger than 9 months remain vulnerable to measles, particularly in areas with high transmission rates and low herd immunity. In this study, we propose an age-stratified, multi-compartmental epidemic model described by ODEs that accounts for maternal immunity decay and reduced vaccine effectiveness due to early administration. For the model without age-stratification, we find the equilibrium points analytically and carry out the local stability analysis. The model estimates age-specific transmission rates by fitting it to yearly incidence data from some high-burden countries. Scenario analysis is performed to evaluate the impact of early vaccination on measles incidence. Moreover, we determine the threshold of vaccine effectiveness reduction that can avert measles cases through pre-ponement of the first dose. Global sensitivity analysis with PRCCs is used to identify critical parameters affecting measles incidence. The findings aim to inform vaccine policy updates and contribute to enhanced global eradication efforts.

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CP16

Phenomenological Bifurcations in Compartmental Stochastic SIS andSIR Models for Epidemiology

We use compartmental models with randomly-fluctuating contact rates to account for the uncertainty in the spread of communicable diseases. Our goal is to study the mechanisms for disease eradication or persistence in a population. We use three different noise types: white, Ornstein-Uhlenbeck (OU) and lognormal OU. We utilize homological bifurcation plots from Topological Data Analysis to automatically study the resulting probability density functions (PDFs) of infected and removed compartments over a range of basic reproduction numbers and relative noise intensities. A peak at zero population in these PDFs is particularly important because it suggests that the disease eradication is mostlikely. Prior studies have hypothesized that for white and OU noise types the peak at 0 is due to their possible negativity, which is in contrast to the non-negative contact rate; our results demonstrate that this is indeed true for most noise intensities since the lognormal OU contact rates, constrained to positive values only, do not demonstrate a 0-peak. We also show that for higher noise intensities, a non-zero peak tends to emerge for high reproduction numbers which corresponds to the disease becoming endemic instead of being eradicated.

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CP17

Deciphering Large-Scale Dynamics in Complex Networks Through Koopman Operator Theory

The dynamics of complex systems, including neuronal activity in the brain and predator-prey relationships in ecosystems, involve high-dimensional, heterogeneous and nonlinear interactions, making it challenging to characterize the relationship between the underlying network structures and emerging large-scale phenomena. Koopman operator theory offers a promising approach, as its spectral analysis identifies fundamental observables of dynamical systems [Brunton et al., SIAM Rev., 2022; Mauroy et al., IEEE Trans. Autom. Control, 2016], but the method has yet to become part of the standard toolbox of network science. This project bridges the gap by computing the Koopman eigenfunctions (KEFs) of various network dynamics to determine the effect of network structure on large-scale behavior. We first compute exact KEFs for feedforward neural networks, which highlight the invariant manifolds and attractors of the dynamics. We then apply Koopman operator theory to the Kuramoto-Sakaguchi model describing nonlinearly coupled phase oscillators on an arbitrary weighted, directed, signed graph to obtain a family of exact KEFs describing the relationship between the graph weights and the stable synchronization manifold. Finally, we compute approximate KEFs for the Lotka-Volterra model on a graph, characterizing the link between network structure and attractor stability. Our work demonstrates the potential of Koopman theory for uncovering structure-dynamics relationships in complex networks.

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CP17

Model Based Learning of Koopman Operator for Complex Mechanical Systems

We present an approach using the Koopman operator for recursive modeling and control of nonlinear systems, adapting the model continuously with new data and optimizing basis functions. Complex, high-dimensional systems require a framework to handle dynamic variations and uncertainties from unmodeled behaviors. Here, recursive updates of the Koopman operator capture critical, unseen behaviors without requiring full retraining. This method functions similarly to a teacher-student model, where an initial physics-based model provides foundational knowledge that is used to develop the Koopman operator and is further refined with real streaming data. This ensures the system gradually learns and adapts to practical conditions. A key feature of this approach is efficient data usage through selective memory retention and subspace updates. As new data streams in, the system assesses its novelty by comparing subspaces using metrics like Grassmannian distance, effectively filtering redundant datasets and optimizing computational resources. This selective update conserves memory and computational capacity, retaining valuable insights and preventing the forgetting of essential patterns. Recursive subspace identification algorithms allow the refining of basis functions by identifying linear representations within observed data that capture essential behaviors. This method offers a more adaptable and resource-efficient way to model and control complex systems in unpredictable environments.

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CP17

Koopmanism for Gait Stability Assessment: Intrinsic Variability and External Perturbation

Quantifying gait stability is essential for assessing fall risk in older adults [Riva F., 2013]. In gait analysis, estimation of stability metrics, such as Lyapunov exponents [Mehdizadeh S., 2017], are commonly used to quantify local stability but may not be able to fully capture the global, non-linear dynamics inherent in gait. In this study, we employ Koopman operator theory to analyze the center-of-mass (CoM) motion capture marker data collected during walking trials. By employing Kolmogorov spectral reconstruction and Extended Dynamic Mode Decomposition (EDMD) algorithm [Zagli N., *preprint*], we compute the operators describing gait stability. This approach allows us to decompose the complex, non-linear gait dynamics into a linear spectral framework, offering insights into the systems stability characteristics and quantifying intrinsic variability in response to real-world perturbations. Preliminary results show that this approach can quantify stable and unstable gait patterns, offering a new perspective on gait stability. This method also provides insights into the effects of intrinsic variability and external perturbations on gait stability, which can contribute to predictive models of fall risk using wearable sensors.

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CP17

Koopman's Approach to Partial Integration of the Kuramoto-Sakaguchi Model on Heterogeneous Graphs

In 1994, Watanabe and Strogatz showed that the Kuramoto model on a complete graph with identical frequencies can be reduced exactly to a system of three equations with $N-3$ integrals of motion [Watanabe et al., Physica D, 1994]. Since then, this partial integrability has been commonly thought to be restricted to identically connected oscillators or groups thereof [Pikovsky et al., Phys. Rev. Lett., 2008], but the exact connectivity prerequisites for preserving these integrals of motion in Kuramoto dynamics on more general graphs have remained elusive. Generalizing and formalizing previous works [Vlasov et al., Phy. Rev. E, 2015; Lohe, J. Math. Phys., 2019], we find the necessary and sufficient conditions to have integrals of motion with the form of cross-ratios in the Kuramoto-Sakaguchi model on any weighted, directed, signed graph. This result reveals a wide range of network motifs between stars and complete graphs that enables partial integration of the dynamics, reducing the system from N equations to $n < N$ equations with $N-n$ integrals of motion. We adopt Koopman theory [Brunton et al., SIAM Rev., 2022] to find the integrals of motions (including new ones), eigenfunctions of Koopman's generator characterizing the synchronization manifold, Lie point symmetries and to perform the partial integration without requiring the Watanabe-Strogatz Ansatz, while providing arguments for Koopman's approach to complex systems [Thibeault et al., Nat. Phys., 2024].

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CP17

Koopman Analysis of Large-Scale Transient Simulation Data on Weather Dynamics

Weather systems, particularly those leading to transient events like torrential rain, exhibit complex, high-dimensional nonlinear dynamics, presenting significant challenges for accurate prediction and model reduction. In this study, we leverage the so-called Koopman mode decomposition (KMD) applied to large-scale simulation data of weather dynamics, focusing on capturing dominant dynamics such as transient behaviors, including heavy rainfall events. By combining spectral analysis of the Koopman operator with dynamic mode decomposition (DMD) algorithms, we can effectively identify dominant spatial-temporal modes that characterize critical phenomena, allowing for a low-dimensional system representation that enjoys accuracy while reducing model complexity. Besides, the Koopman operator can have a continuous spectrum, a generic feature of short-time dynamics, making it particularly well-suited for capturing the transient behaviors inherent in weather dynamics. We hope this approach will be a potential framework for analyzing transient weather patterns, such as torrential rain, enhancing both the efficiency and accuracy of weather prediction and control.

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CP18

Perturbations of Non-Autonomous Second-Order Abstract Cauchy Problems

In this talk we present time-dependent perturbations of second-order non-autonomous abstract Cauchy problems associated to a family of operators with constant domain. We make use of the equivalence to a first-order non-autonomous abstract Cauchy problem in a product space, which we elaborate in full detail. As an application we provide a perturbed non-autonomous wave equation. Autonomous second-order abstract Cauchy problems which often occur in the context of wave equations, have been studied intensively by several authors in the past. In contrast to the first-order problem, where (classical) solutions are given by C0-semigroups, one needs another solution concept for the second-order case, the so-called cosine and sine families. Similar to the HilleYosida generation theorem for strongly continuous semigroups, one can also characterize generators of cosine families. Non-autonomous second-order abstract Cauchy problems have been studied first by Kozak and later on by Bochenek, Winiarska and Lan, just to mention a few. The classical idea helps to reduce the non-autonomous second-order abstract Cauchy problem again to a first-order problem. The goal is to establish a bounded perturbation result for non-autonomous second-order abstract Cauchy problems. As mentioned above, we also discuss the non-autonomous wave equation as an example.

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CP18

Global Attractors and Singular Limits for Dynamical Systems Generated by Various Transmission Problems for Elastic Beams.

We investigate dynamical systems generated by nonlinear systems of PDEs describing dynamics of two beams with rigid contact [see, T. Fastovska, Global attractors for a full von Karman beam transmission problem. Commun Pure

Appl Anal. (2023) 22:112058. doi: 10.3934/cpaa.2023022 and T. Fastovska, D. Langemann, I. Ryzhkova, Qualitative properties of solutions to a nonlinear transmission problem for an elastic Bresse beam, Front. Appl. Math. Stat 10:1418656 (2024), doi:10.3389/fams.2024.1418656]. We consider various models for the beams: the Bresse model for initially curved shearable beams and the full von Karman model for initially straight non-shearable beams. We also assume various types of dissipation acting on one part of the beam. We show the existence of compact global attractors for the systems and describe their structure. Moreover, we show that if the curvature tends to zero, solutions to the Bresse transmission problem tend to the solutions of two problems. The longitudinal displacements in this case tend to solutions of a transmission problem for a wave equation and the transversal displacements and shear angles tend to solutions to the Timoshenko problem. In case curvature tends to zero and shear moduli tend to infinity, the longitudinal displacements tend to solutions of a transmission problem for a wave equation and the transversal displacements to solutions of a transmission Kirchhoff problem with rotational inertia.

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CP18

Decay Rates of Neutral, Collisionless Plasmas

Collisionless plasmas arise within a variety of settings, from magnetically confined plasmas in laboratories to space plasmas in planetary magnetospheres and solar winds. The fundamental electrostatic model that describes such phenomena is a system of nonlinear PDEs known as the Vlasov-Poisson (VP) system. After providing some background information concerning VP, recent results regarding the large-time behavior of solutions will be introduced. These results establish a variety of limiting self-similar behaviors for the associated charge density and electric field with time decay rates up to any integer order. This behavior is physically attributed to the degree of charge cancellation amongst moments of different particle species within neutral plasmas.

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CP18

On the Kinetic Description of the Objective Molecular Dynamics

We introduce a multiscale hierarchy framework for objective molecular dynamics (OMD), a reduced order molecular dynamics with certain symmetry, that connects it to the statistical kinetic equation, and the macroscopic hydrodynamic model. In the mesoscopic regime, we exploit two interaction scalings that lead to either a mean-field type or a Boltzmann-type equation. It turned out that, under the special symmetry, the mean-field scaling results in an oversimplified dynamics that extinguish the underlying molecular interaction rule, whereas the Boltzmann scaling yields a meaningful reduced model called homo-energetic Boltzmann equation. At the macroscopic level, we also derive the corresponding Euler and Navier-Stokes systems by conducting a detailed asymptotic analysis. The symmetry again significantly reduces the complexity of the resulting hydrodynamic systems.

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CP18

Instability of Uniform Oscillations in the Spatially Extended May-Leonard System

It is known that small-amplitude spatially uniform nonlinear oscillations can be subject to a modulational instability. The spatial instabilities of strongly nonlinear oscillations are still less explored. In [1], spatial instabilities of oscillations close to a homoclinic orbit have been studied. We investigate the stability of uniform oscillations in the spatially extended May-Leonard system with non-equal diffusion coefficients for different species. For critical values of parameters, the system has a family of time-periodic solutions that spreads from small-amplitude oscillations to strongly nonlinear oscillations close to a heteroclinic cycle. In the case of a model symmetric to a cyclic permutation of variables, the oscillatory solutions can be found analytically. By means of a special kind of perturbation theory, we show analytically that the oscillations are never unstable with respect to longwave spatial modulations. However, in a definite region of the values of diffusion coefficients, oscillatory solutions sufficiently close to the heteroclinic cycle can be unstable with respect to a period-doubling instability with a finite wavenumber. The generalization of the obtained results to the case of an asymmetric model is discussed. 1.M. Argentina, P. Coullet, E. Risler, Self-parametric instability in spatially extended systems, Phys. Rev. Lett. 86 (2001) 807-809.

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CP18

Slow Manifolds in Multiscale PDEs and their Application

In this talk I will introduce the concept of slow manifolds as an approach to reduce the complexity of a multiple timescale PDE system. Roughly speaking the idea is that in a fast slow system the fast variable approaches a state in which its dynamics are only determined by the slow variable and therefore one can reduce the system to a self-contained and lower dimensional equation which only depends on the slow variable. In the first part of this talk I will present the main result for a generalization of the Fenichel- Tikhonov theory in this infinite dimensional setting. The second part of this talk focuses on the application of the results to a generalized Klausmeier model. This talk is based on joint work with Christian Kuehn (TUM)

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CP19

Stochastic Simulation and Prediction of Mechanical Behavior at Small Scale Using Gaussian Process-Driven Models

Predicting mechanical responses at small scale in metallic materials is critical for taking advantage of recently developed nanometallic applications. Especially, those noble materials have exhibited sample size dependence and stochastic response, which makes the prediction of mechanical properties very challenging. This work introduces a Gaussian Process Regression (GPR)-based framework to simulate and predict the strain-stress curve under uniaxial loading, enabling robust forecasting of strain bursts and overall mechanical response dynamics. To obtain physically robust data, dislocation dynamics modeling has been performed, producing the strain-stress curve along with the information on dynamics evolution of dislocations. The mesoscale dislocation dynamics model could provide a unique opportunity to investigate the stochastic dynamic process of dislocation interactions together with macroscopic materials response. Afterward, the GPR model serves both as a predictive tool for anticipated strain bursts and as a generator of synthetic strain-stress trajectories that align with observed stochastic variability. This approach not only provides probabilistic bounds for future strain bursts but also enhances the interpretability of complex mechanical behaviors in materials science. The frameworks predictions are validated against experimental datasets, demonstrating its effectiveness in reliably capturing the nuanced stochastic dynamics of material deformation and failure.

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CP19

Reducing Parameter Count in High-Dimensional Systems of Stochastic Differential Equations

Biophysical models frequently suffer from a proliferation of free parameters, due to the inherent complexity of their corresponding biological systems. While some free parameters may be fixed through careful measurements, many remain experimentally inaccessible. Suitably, we develop methods to reduce the number of free parameters in a computational model, demonstrating them on a stochastic biophysical model for hearing mechanics. Starting with a comprehensive model for auditory hair cells, we quantitatively rank each free parameter by its influence on selected, core properties of the model. With the resultant ranking, we fix most of the low-influence parameters, yielding a low-parameter model with optimal predictive power. We validate this reduced theoretical model with maximum-likelihood fits to experimental recordings. By developing robust parameter-reduction methods, we alleviate the risk of over- and under-fitting data, thus enhancing the predictive power of our model. Further, by determining the high-influence free parameters in our numerical model, we illuminate the key biophysical elements in our biological system. Though we demonstrate our parameter-reduction methods with a specific model, they can be readily generalized to simplify other high-dimensional models.

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CP19

Random Dynamical Systems Approach to Study (non-IID) Repeated Interaction Dynamics and Random MPS

A discretization of the dynamics of an open quantum system is the repeated interaction model, where one assumes that the system interacts with IID copies of the environment or a collection of smaller units (ancillas). However, using methods in random dynamical systems (RDS) one may study repeated interaction dynamics for the non-IID case. In discreet parameter, a RDS is a measure-preserving system (Ω, Pr, θ) together with a measurable space $(X, \mathcal{B})$ and a measurable map $f : \mathbb{Z} \times \Omega \times X \to X$ that satisfy the cocycle property: $f(n+m, \omega, x) = f(m, \theta^n(\omega), f(n, \omega, x))$, for all $x \in X$. In the context of repeated-interactions, we assume that the interactions are given by a stationary sequence of super-operators, $(\phi_n)_{n\in\mathbb{Z}}$, defined on the measure-preserving system (Ω, Pr, θ) where $\phi_n = \phi_0 \circ \theta^n$. Thus, the dynamic propagators, $\Phi_\omega^{(n)} = \phi_n^\omega \circ \ldots \phi_1^\omega$, satisfy the cocycle property for quantum states. We study the asymptotic behavior of $\Phi^{(n)}$ using RDS tools and obtain limiting results for both the discrete-parameter case and the continuous time dynamics. Furthermore, we obtain a class of matrix product state (MPS) that are distributionally translation invariant (a generalization of uniform MPS). We obtain decay rates for correlations of expectation of local observables in thermodynamic limit.

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CP19

Analyzing Uncertainties in Dynamic Systems with Reference to the Fokker-Planck Equation

We discuss a modeling perspective on uncertainty quantification (UQ) in dynamical systems with the deterministic system described by the initial-value problem

$$\dot{q} = f(q), \quad q(0) = q_0 \in \mathbb{R}^d, \quad d \geq 1.$$

For an uncertain initial state and additional uncertainties in the system, the time-dependent states are a stochastic process $(Q(t))_{t\geq 0}$. Under some regularity conditions, the random variables $Q(t)$ are described by their probability densities $\varrho(\cdot, t) \in L^1_{1+}(\mathbb{R}^d) = \{\eta : ||\eta||_{L^1(\mathbb{R}^d)} = 1, \ \eta \geq 0 \text{ a. e.}\}$ and the time evolution of the density is given by the Fokker-Planck equation

$$\frac{\partial}{\partial t}\varrho = -\nabla \cdot [f(x)\,\varrho] + \nabla \cdot [D\nabla\varrho] \quad \text{with} \quad \varrho(0, x) = \varrho_0(x).$$

Although solving the Fokker-Planck equation is not achievable in most realistic applications due to the large dimensions, we use it as a reference for UQ models, which approximate $\varrho(t, x)$ by Gaussians. These UQ models form a model family with the Fokker-Planck equation as the model of highest fidelity or ground truth. In analogy to the numerical solution of ODEs and their numerical errors, we investigate different UQ models for benchmark examples and derive indicators for the approximation quality and for step-size control in numerical update procedures.

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CP20

Neural Mass Models of Interhemispheric Oscillations in Granular Retrosplenial Cortex

In vivo recordings of local field potential (LFP) from granular retrosplenial cortex (RSg) exhibit coexisting gamma (30-80 Hz) and spline (100-160 Hz) oscillations, coupled to distinct phases of the background theta (5-12 Hz) rhythm. Remarkably, bilateral recordings reveal that gamma and splines exhibit divergent interhemispheric phase relationships, with gamma in-phase across hemispheres and splines anti-phase across hemispheres. Motivated to understand these experimental observations, we study a minimal interhemispheric model network composed of quadratic integrate-and-fire (QIF) neurons, arranged as a pair of delay-coupled excitatory-inhibitory modules. Using the Ott-Antonsen reduction to obtain exact mean-field equations, we perform numerical bifurcation analyses to expose the bifurcation structures governing network dynamics in the presence and absence of theta-rhythmic periodic forcing. We demonstrate that experimental observations in RSg may be explained parsimoniously by theta-timescale alternation between oscillations generated by PING- and ING-like mechanisms, with interhemispheric conduction delays enforcing the divergent phase relationships even in presence of rhythmic inputs. Our work presents hypotheses for rhythmogenesis in RSg, compares the statistics of experimental recordings to those generated by the model, and constructs bifurcation diagrams for the interhemispheric networks which can inform the design of future optogenetic experiments.

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CP20

Dynamics of a 2-D Discrete Neuron Map: Nodal and Network Analysis

We introduce a novel 2-D discrete neuron map, denoted by map H(x, ?), formed by incorporating electromagnetic flux into a one-dimensional Chialvo map. Our exploration encompasses a comprehensive study of the dynamical aspects of the map, covering fixed points, bistability, various bifurcations, S-shape attractor, firing patterns, pathways leading to chaos, including the period-doubling to chaos and reverse period-doubling to chaos. We validate the results by employing various dynamical techniques (like Lyapunov exponent diagrams, phase portraits, calculating the correlation dimensions, and basins of attraction). Beyond single-neuron analysis, we extend our investigation to a network of neurons governed by the map H(x, ?), specifically a ring-star network configuration. This broader examination reveals various dynamical states within the network, including synchronous, asynchronous, and chimera states. Finally, we present simulations exploring different coupling strengths to uncover diverse wavy patterns and clustered states within the network dynamics.

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CP20

Multiple-Timescale Modeling of Altered Sodium Channel Gating in the Case of An Epilepsy Mutation.

Dravet syndrome is a severe epilepsy that begins in the first year of life, characterized by drug-resistant seizures, cognitive delay and a risk of early death. Most cases are due to mutations of NaV1.1, a sodium channel expressed in fast-spiking (FS) inhibitory neurons. The hypothesized initial pathologic mechanism involves impaired activity of those neurons leading to network hyperexcitability, but the details are unclear. Mutant NaV1.1 channels are either non-functional or with altered gating properties. We focus on the latter, less studied, by investigating how altered gating impairs neuronal activity in the case of the A1783V mutation. Based on recordings, Layer et al. show that A1783V alters the voltage dependence of channel activation, as well as the voltage dependence and kinetics of slow inactivation. They conclude from modeling that, of these, altered activation has the most impact on reducing spiking frequency. Using the same conductance-based model, tailored to FS inhibitory neurons dynamics, we examine how the three alterations affect susceptibility to depolarization block, another dysfunction aside from frequency reduction. We look deeper into slow inactivation, exploiting the timescale difference with the rest of the system. We suggest that its alteration might also play a role. Finally, we study factors (temperature, potassium concentration) that could lower the threshold for seizure onset. Our predictions can be tested with ramped electrophysiology protocols.

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CP20

Intracellular and Network-Scale Modeling of the Effects of Focal Axonal Swelling in the Visual Cortex

Traumatic brain injuries have been associated with the development of axonal varicosities along some of the neurons in affected brain tissues. Referred to as focal axonal swelling (FAS), these defects have been shown to have significant impact on the conduction of electrical current along the axon length due to complexity arising from cable width variation. Mathematical modeling indicates the possibility of substantial interactions between action potentials traveling across such a deformation in a damaged cell. We give a brief overview of our approaches for getting past the computational challenges involved in simulating the transmission of action potentials along a neural axon with functionality that is compromised in this way, and we provide a look ahead at assessing the effects of such injuries on network dynamics paradigms arising in certain areas of the visual cortex.

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CP20

From Spiking Networks to Differential Equations: A Model Reduction Framework for Neural Dynamics

Spiking neuronal networks (SNNs) offer a biologically inspired yet mathematically complex framework for modeling neural dynamics. So far, reducing SNNs to differential equations remains an open problem. The primary challenges are twofold: 1) the rich, parameter-sensitive SNN dynamics, and 2) the singularity and irreversibility of spikes. In this talk, I present a Markovian model reduction framework that maps finite-size SNN dynamics onto discrete-state ordinary differential equations (dsODEs) while minimizing information loss. The key assumption is fast self-decorrelation of synaptic conductances, leading to a hierarchy of tractable approximations that significantly reduce dimensionality. The resulting dsODEs remain accurate across a broad parameter range. They capture essential features such as high-frequency partial synchrony, metastability, and finite-size effects. Furthermore, the detailed structure of bifurcations, including transitions between dynamical regimes, is preserved under parameter variations. This approach provides a principled way to bridge the gap between spiking networks and differential equations. More broadly, it contributes to model reductions in complex systems, where balancing accuracy and tractability remains a key challenge.

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CP21

The Problem of Infinite Information Flow

Learning the causal relations among interacting entities has been a fundamental pursuit since antiquity. From an information theoretic perspective, several numerical methods with convincing heuristics have been proposed, leading to successful learning results. In particular, the conditional mutual information (cMI) quantifies the deviation from conditional independence between two random variables given a third one and mathematically underpins the well-known transfer entropy and generalizations such as causation entropy. In typical situations relevant to dynamics, we prove that the transfer entropy is infinite, which fails to distinguish between the less/more amounts of information flowing through more/less chaotic maps. We also illustrate how discretization can resolve this problem.

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CP21

Reduced-Order Neural Estimation for Spatiotemporal Dynamics Without Bptt

Real-time state estimation for spatiotemporal systems using sparse sensor observations is difficult due to the high dimensionality of the governing partial differential equations (PDEs). Promising recent approaches combine a reduced-order model (ROM) of the dynamics with an observation update module trained offline using backpropagation through time (BPTT). However, the complexity of the algorithmic structure of these hybrid estimators makes the training process very unstable. To address this challenge, we introduce the reduced-order neural estimator (RONE), a hybrid state estimation framework designed to be easily trainable offline without BPTT. This is made possible by a greedy loss function that approximates the error between the estimate and the ground truth using a single-step forward pass through the RONE. We compare the RONE with various model-based and/or data-driven baseline estimation algorithms on several PDEs, demonstrating that the RONE trains at least five times faster than the baselines while yielding comparable estimation accuracy. Our methodology paves the way for lightweight estimation architectures that can be trained on-the-fly to adapt to environment changes.

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CP21

Hydrodynamic Modeling Using Physics Informed Machine Learning Method

Hydrological models are essential tools for understanding and predicting water system behavior across various applications. This study introduces a physics-informed machine learning framework, incorporating both data and the physics of hydrological applications, specifically we consider the computationally intensive dam-break flood problem. Our Physics-Informed Neural Networks (PINNs) framework aims to reduce computational costs compared to classical numerical methods. We demonstrate the effectiveness of our PINNs model, trained with numerical solutions of the Shallow Water Equations, in accurately predicting the long-term dynamics of one-dimensional dam-break floods. The model's performance is evaluated against a Data-Driven Neural Network and a Hybrid Neural Network, showing that the PINNs model outperforms the HNN in generalizing and predicting wave propagation. Although the Data-Driven Neural Network fits the training data closely, it fails to generalize to unseen data, underscoring the limitations of purely data-driven approaches. Our findings suggest that while data-driven models are useful, they require extensive additional data for more complex, real-world scenarios, such as two- and three-dimensional problems. PINNs, on the other hand, scales efficiently with problem dimensions, eliminating the need for mesh construction. Although the current study is limited to frictionless horizontal dam-break problems, our method shows promise for broader applications.

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CP22

Bifurcation Studies of Nonlinear LC Circuit Containing Josephson Junction

This work explores the dynamics of nonlinear LC circuits involving Josephson junctions, which act as nonlinear inductors. A Josephson junction, consisting of two superconductors separated by an insulator, allows Cooper pairs to tunnel through, exhibiting the Josephson effect. One can use the Josephson junction as a nonlinear inductor element. This talk considers a nonlinear LC circuit containing a capacitor and the Josephson junction connected in parallel. The equation of motion for such a nonlinear LC circuit is as

$$\ddot{\Phi} + \omega_0^2 \sin(\Phi) = 0,$$

where Φ is the magnetic flux, $\omega_0 = \sqrt{\frac{|I_c|}{C}}$ is the natural frequency, C is the capacitance, and I_c is the critical current. For negative values of the I_c, the junction is called π Josephson junction. This talk addresses the gap of stability analysis for negative and positive values of I_c, which is lacking in the literature. Using a canonical transformation, we modeled the system in forward and backward propagating modes. In a weak coupling framework, we develop a reduced model. Stability analysis of this model, with the critical current as a parameter, reveals a pitchfork bifurcation in a two-dimensional system, where a fixed point splits into an uncountable number of fixed points, forming a circle. This work may inspire further exploration of pitchfork bifurcation in higher dimensions, where a stable fixed point can break into unaccountably many fixed points.

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CP22

Dynamics and Periodicity Conditions for the Integrable Boltzmann System

Consider a simple mechanical system proposed by Boltzmann in the 1860s: a massive particle moves in a gravitational field with a linear boundary between the particle and the center of gravity. Reflections off the boundary are absolutely elastic and obey the billiard reflection law: angles of incidence and reflection are congruent. This system was recently shown by Gallavotti and Jauslin to have a second integral of motion. We study its dynamics and prove the existence of caustics, Cayley-type periodicity conditions, and more. This is joint work with Milena Radnović (University of Sydney).

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CP22

Geometrical Structure of Bifurcations During Spatial Decision-Making

How animals navigate and perform directional decision-making while migrating and foraging is an open puzzle. We have recently proposed a spin-based model for this process, in which each optional target presented to the animal is represented by a group of Ising spins. These spins have all-to-all connectivity with ferromagnetic intra-group interactions. The inter-group interactions take the form of a vector dot product, depending on the instantaneous relative and deformed angle between the targets. The deformation of the angle in these interactions enhances the effective angular differences for small angles, as was found by fitting data from several animal species. Here, we expose the rich variety of trajectories predicted by the mean-field solutions of the model for systems of three and four targets. We find that, depending on the arrangement of the targets, the trajectories may exhibit an infinite series of self-similar bifurcations or have a space-filling property. The bifurcations along the trajectories occur on 'bifurcation curves,' that act as attractors of the mean-field trajectories and determine their overall nature. The angular deformation, found to fit experimental data, is shown to greatly simplify the trajectories. This work demonstrates the rich space of trajectories that emerge from the model.

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CP22

Constraining Limit-Cycle Oscillations Using the Recovery Rate

Hopf bifurcations occur in a variety of engineering domains, ranging from fluid-structure interaction to combustion. Despite recent advances in predicting these bifurcations and their associated limit-cycle oscillations (LCOs), preventing undesired LCOs during system design remains a challenge. Incorporating LCO predictions as constraints in numerical design optimization offers a promising solution. However, existing LCO constraints face scalability issues in complex systems due to: i) the computational challenges associated with bifurcation diagram calculations for large-scale models; ii) non-smooth constraints arising from focusing on a single instability mechanism, which prevents the use of gradient-based algorithms; and iii) the risk of over-constraining the design. This talk introduces a constraint that addresses these limitations by bounding the systems recovery ratean indirect approach to preventing undesired LCOs. This approach eliminates the need for bifurcation diagrams and avoids enforcing unnecessary design requirements. Additionally, by aggregating recovery rates across operating conditions and response amplitudes, it provides a smooth, scalar constraint that is independent of the critical instability mechanism and compatible with gradient-based algorithms. The effectiveness of the approach is demonstrated through a design optimization example of a nonlinear aeroelastic system.

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CP22

Gaussian Process Phase Interpolation for Estimating the Asymptotic Phase of a Limit Cycle Oscillator from Time Series Data

Rhythmic activity commonly observed in biological systems is typically modeled as limit cycle oscillators. Phase reduction theory provides a useful analytical framework for elucidating the synchronization mechanism of oscillators. In essence, this theory describes the dynamics of a multi-dimensional nonlinear oscillator using a single variable, called the asymptotic phase. Estimating the asymptotic phase from the observed data is crucial for understanding and controlling the rhythmic phenomena in the real world. In this study, we propose Gaussian Process Phase Interpolation (GPPI), a novel method for estimating the asymptotic phase from time series data. GPPI first evaluates the asymptotic phase on the limit cycle and then estimates the asymptotic phase outside the limit cycle using Gaussian process regression. The proposed method captures a variety of functions and it is easily applicable even as the dimension of the system increases. We test GPPI on simulation data from the Stuart-Landau oscillator and the Hodgkin-Huxley oscillator. Our results show that GPPI accurately estimates the asymptotic phase even in the presence of high observation noise and strong nonlinearity. Additionally, we demonstrate that GPPI is an effective tool for data-driven control of a Hodgkin-Huxley oscillator. Therefore, the GPPI method will facilitate the data-driven modeling of the limit cycle oscillators.

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CP23

Enhancing Predictions of the First Ice-Free Arctic Summer Through Modified Energy Balance Modeling

This talk presents an adaptation of the Daily Budyko Energy Balance Model to improve predictions of the first ice-free summer in the Arctic, with a focus on incorporating direct thermal interactions between sea ice and ocean. The model modifications aim to better capture the dynamics of seasonal melting and refreezing by introducing additional heat transfer mechanisms. This approach is intended to explore how localized thermal processes may influence the timing of ice-free conditions and the stability of the Arctic

ice cover. By emphasizing multiscale interactions within the model, this work seeks to advance our understanding of Arctic sea ice dynamics and contribute to more accurate projections of critical climate tipping points in polar regions.

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CP23

Complex Dynamics of a Delay Predator-Prey Model with Holling-Type Functional Responses.

We study a classical predator-prey model with Holling type 1 and 2 functional responses respectively, incorporating a delay factor to account for the natural death of predators within tau units of time after predation. Our goal is to understand how the delay changes the stability of our models. Taking the delay tau as our bifurcation parameter, the model with Holling type 1 model reveals infinitely many Hopf bifurcation points, with periodic orbits of gradually decreasing periods. The model with Holling type 2 model unfolds the presence of transcritical and nested Hopf bifurcation, leading to the termination and formation of limit cycles within certain thresholds of the growth capacity parameter. Numerical simulations using ddebiftool and dde23 verify our analytic results.

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CP23

Effects of Hyperparasitism in Semi-Discrete Host-Parasitoid Population Dynamic Models

A parasitoid is an organism that spends most of its lifecycle attached to or inside the host. Unlike an actual parasite, the parasitoid eventually kills the host. During a particular season of the year, known as the vulnerable period, the parasitoid injects eggs into the host larvae. Parasitoid larvae then emerge from the host, effectively killing it. Early models of this phenomenon include the discrete-time Nicholson-Bailey model, which is known to be unstable (i.e., coexistence is impossible). In this paper, we implement relevant changes during the vulnerable period using a semi-discrete framework that includes an obligate hyperparasitoid population. Oviposition by the parasitoid and hyperparasitoid populations is assumed to be asynchronous. We consider several forms of parasitism including combinations of constant and functional response attack rates as well as variable rates of attack. We find that a feasible coexistence regime exists for when the hyperparasitoid attack is more efficient than that of the parasitoid. We also explore the addition of a host refuge and its influence on the coexistence regimes of all three species.

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CP23

Coupling Fear and Group Defense in Prey, and Allee Effect in Predator: A Global Dynamics Approach

In this article, we explore the dynamical behavior of a predator-prey system where prey populations decline due to both direct predation and fear of predators. This fear causes prey to invest time in avoidance strategies, reducing the time available for reproduction. The Allee effect in predators, where low population density restricts reproduction and survival, further complicates predator dynamics. Taking these ecological factors into account, we introduce a two-dimensional model that includes fearful prey, predators affected by the Allee effect, and a group defense functional response. The system undergoes co-dimension one bifurcations, such as saddle-node, Hopf, homoclinic, and saddle-node bifurcation of limit cycles, as well as co-dimension two bifurcations like Bautin and Bogdanov-Takens, illustrating the complex dynamics of the system. By mapping the bi-parametric plane defined by the Allee effect and fear parameters, distinct regions highlighting multi-stability (bi-stability and tri-stability) and global stability are identified. These results suggest that predator survival depends on initial population sizes, with the intensity of fear and Allee effect strength playing key roles in predator persistence or extinction. The transversality and genericity conditions for all bifurcations were verified and validated through numerical simulations and graphical illustrations.

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CP23

A Manifold Learning Perspective on Surrogate Modeling of Nitrate Concentration in the Kansas River

A non-linear surrogate model of nitrate concentration in the Kansas River (USA) is described. The model is an (almost) Piecewise Linear response surface that provides a mean field approximation to the dynamics of the measured data for nitrate plus nitrite (target product) correlations to turbidity and chlorophyll-a concentrations (input variables). The method extends the United States Geological Surveys linear procedures for surrogate data modeling allowing for better approximations for river systems exhibiting algal blooms due to nutrient-rich source waters. The model and visualization procedures illustrated in the Kansas River example should be generally applicable to many medium-size rivers in agricultural regions.

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CP24

Dynamic Modeling of Washing Machine Leg-Ground Contact to Predict the Walking Phenomenon

This study investigates the walking phenomenon in washing machines, focusing on modeling the leg and ground contact dynamics that influence stability during opera-

tion. A detailed multibody washing machine model is developed to simulate dynamic interactions between the leg and ground under varying frictional conditions. The initiation of walking is analyzed by examining the effects of leg stiffness, damping, and contact friction on overall stability. To achieve this, a local dynamic leg model based on a user-defined force element is integrated into a multibody dynamic model using Adams software. Experimental measurements are used to determine key parameters, including the damping and stiffness properties of the leg and the friction coefficient at the contact interface between the leg and a ceramic surface. Additionally, experimental validation testsincluding stability assessments under operational loading conditionsshow strong agreement with the simulation results, verifying that the proposed models can accurately predict the onset of walking behavior. This research provides valuable insights into the complex dynamics of washing machine stability, highlighting the influence of leg-ground contact properties. The findings highlight potential adjustments in leg and ground contact design parameters that may help reduce the walking tendency and improve the washing machine's stability, addressing user and industry expectations for reliability and robustness.

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CP24

Balls, Cans, and Discs: Why Newtonian Mechanics Is Still in a Spin

I consider three problems in mechanics involving rotation. Along the way, I will discover some new effects, formalise some old ones, and ask some questions about dissipation. In basketball, one of the most exciting phenomena is when the ball rolls around the rim of the hoop, and the players cannot predict whether the ball will fall inside or outside the basket. For some initial conditions, the fate of the ball depends on the friction model used. Balance an empty can on a horizontal surface and release it. The can rocks downwards rotating about the contact point. It appears to bounce and then rocks back up again, as the contact point moves rapidly around the rim of the can. Using the Frobenius method and classical asymptotic analysis, there is very accurate explicit solution to problem, in agreement with experiments. Take a coin and spin it vertically on a flat, hard surface. The coin starts to fall, and its rate of rotation increases. The motion is accompanied by a whirring noise, followed by a sudden bang, as the coin comes to a halt flat on the surface. Why does the disk halt? Ill show some experimental evidence for the commercial Euler disk where the surface material influences the disk dynamics and show that the disk can continue to rotate after falling flat, where theory and experiment agree. Ill bring along the Euler disk for you to experiment yourself.

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CP24

Island Myriads in Periodic Potentials

A phenomenon of emergence of stability islands in phase-space was identified for two periodic potentials with tiling symmetries, one square and other hexagonal, as inspired by bidimensional Hamiltonian models of optical lattices. The structures found, here named as island myriads, resemble web-tori with notable fractality and arise at energy levels reaching that of unstable equilibrium points. In general, the myriad is an arrangement of concentric island chains with properties relying on the translational and rotational symmetries of the potential functions. In the square system, orbits within the myriad come in isochronous pairs and can have different periodic closure, either returning to their initial position or jumping to identical sites in neighbour cells of the lattice, therefore impacting transport properties. As seen when compared to the generic case, i.e. the rectangular lattice, the breaking of square symmetry disrupts the myriad even for small deviations from its equilateral configuration. For the hexagonal case, the myriad was found but in attenuated form, mostly due to extra instabilities in the potential surface that prevent the stabilization of orbits forming the chains.

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CP24

An Extension of the Poincar-Birkhoff Theorem to Systems Involving Landesman-Lazer Conditions

We provide multiplicity results for the periodic problem associated with Hamiltonian systems coupling a system having a Poincar-Birkhoff twist-type structure with a system presenting some asymmetric nonlinearities, with possible one-sided superlinear growth. We investigate non-resonance, simple resonance and double resonance situations, by implementing some kind of Landesman-Lazer conditions.

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CP24

An Oscillators-Barrier Hamiltonian Impact System

We present a class of pseudo-integrable dynamical systems, the Hamiltonian impact system of a particle on a plane with a separable unimodal potential and a horizontal barrier - the oscillators-barrier problem. This system is not integrable in the Liouville-Arnold sense as the phase space is foliated by surfaces of genus 1 and 2, exhibiting topological singularities along the foliation. We establish the conjugation of the return maps along the foliation to a family of interval exchange transformations, a rich class of maps that are piecewise symplectic and globally area-preserving, exhibiting complex dynamical behavior due to the presence of discontinuities. We explore small perturbations of this family of maps and of related maps and discuss their symmetries and their periodic orbits. Finally, we demonstrate the absence of invariant dividing curves, a result that diverges from the traditional persistence of KAM curves in perturbed smooth twist maps.

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CP25

A Quadrature Technique for Efficient Kalman Filtering with Model-Space Covariance Localization

In atmospheric applications of ensemble data assimilation, covariance localization is crucial for mitigating the effects of spurious correlations between model variables, as well as for preventing ensemble collapse. Certain observation types require localization to be done in model space, a computationally demanding task which involves various trade-offs between accuracy, runtime, and memory usage. This talk introduces a new algorithm for model space localization which achieves a favorable trade-off between these three factors by combining modern techniques from numerical quadrature, Krylov subspace iteration, and matrix function evaluation. This algorithm is compatible with a wide variety of spatial and spectral covariance localization schemes, is parallelizable, and is built upon linear-algebraic primitives whose accuracy is backed up by strong error analyses. We will present the results of numerical experiments comparing its accuracy and efficiency to existing methods such as the gain-form ensemble transform Kalman filter (GETKF). We will also discuss recent efforts to test this algorithm on large-scale atmospheric forecasting problems using the Joint Effort for Data Assimilation Integration (JEDI) and the Model for Prediction Across Scales (MPAS).

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CP25

Sparse Dynamics Using Symbolic Neural ODEs

We present a novel machine learning approach to estimate sparse models for dynamical systems from time-series data. We use a deep learning inspired architecture to generate a vector field as a function of state. This model is numerically integrated to best approximate state data at subsequent points in time over a prediction horizon. For numerical tractability, we optimize for the mean absolute error over this prediction horizon that we increase progressively with training. Done over multiple time-steps, we find that the neural network - with operations like exponentiation and multiplication under multiple compositions - estimates models that are relatively stable compared to regression over the vector field alone. Using a sparsity promoting regularization, we find models that generalize beyond the training datasets. We demonstrate identification of dynamical systems with a variety of asymptotic characteristics like stable and unstable fixed points, periodic orbits, limit cycles and even chaotic attractors. And even if the estimated model is not of the desired sparsity, we show that the mean and standard deviation of the estimated black-box model are bounded by the training error. For chaotic time-series data, we also find the Lyapunov exponents are in good agreement.

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CP25

Data-Driven Sparse Identification with Adaptive Function Bases

Interpretable data-driven methods have proven viable for deriving kinetic equations directly from experimental data. However, such numerical methods are inherently susceptible to noise, which affects the sparsity in the resulting models. In order to promote such a sparsity condition, finding the optimal set of basis functions is a necessary prerequisite, but yet a challenging task to determine in advance. We here present our in-house developed `ddmo` software, which allows a precise control over the space of candidate constituent terms. Such a complete framework comprises two main novel features. The first feature permits to include parametric functions in the library. Secondly, an adaptive library sizing routine that progressively adds or removes elements based on the learning from the dataset. We show a practical application of our algorithm tailored at identifying Langmuir-Hinshelwood mechanisms from experimental data.

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CP25

Weak Form Model Selection for Structured Populations

In the context of population dynamics, the identification of effective model ingredients, e.g., fecundity and mortality rates, is generally a complex and computationally intensive process, especially when the dynamics are heterogeneous across the population. In this talk, we propose a method of selecting proper model ingredients from a library of basis functions for structured populations. This method uses extensions of the recent WENDy and WSINDy methods to select the best fitting ingredients from noisy time-series histogram data. Several test cases are considered demonstrating the method's performance for different previously studied models including age and size structured models. Through these examples, we examine both the advantages and limitations of the method, with a particular focus on how the temporal and structural resolution of the dataset influences the accuracy of the model.

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CP25

"PINN Combined with Time-Fractional Black-Scholes Equations for Capturing Options Dynamics" (Preliminary Report)

It is known that the prices of certain financial instruments exhibit memory effects and these phenomena could be modeled by time-fractional Black-Scholes equations (tfBSE). Physics-Informed Neural Networks (PINN) is a promising tool for calibrating financial math models, although challenges need to be addressed, especially in modeling American options. In this talk, we present our preliminary results on combing PINN with tfBSE for capturing the dynamics of American options. Both simulated data and market examples will be used to validate our methods.

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CP25

Wlasdi: Weak Form Latent Space Dynamics Identification

Recent work in data-driven modeling has demonstrated that a weak formulation of model equations enhances the noise robustness of a wide range of computational methods. In this presentation, we demonstrate the power of the weak form to enhance the LaSDI (Latent Space Dynamics Identification) algorithm, a recently developed data-driven reduced order modeling technique. We introduce a weak form-based version of WLaSDI (Weak-form Latent Space Dynamics Identification). WLaSDI first compresses data, then projects onto the test functions and learns the local latent space models. Notably, WLaSDI demonstrates significantly enhanced robustness to noise. WLaSDI obtains the local latent space using weak-form equation learning. Compared to the standard sparse identification of nonlinear dynamics (SINDy) used in LaSDI, the variance reduction of the weak form guarantees a robust and precise latent space recovery, hence allowing for a fast, robust, and accurate simulation.

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CP26

Ferrofluid Drop in An off-Centered Radial Magnetic Field: Dynamics and Pattern Formation

We investigate the dynamic and morphological behaviors of a ferrofluid drop initially located at the center of a Hele-Shaw cell, under the influence of an off-centered radial magnetic field. Previous studies have demonstrated that when the center of the cell coincides with the center of the radial magnetic field, symmetric, stationary, star-like ferrofluid shapes may arise. In this work, we employ a perturbative, second-order mode-coupling approach to examine the changes in the emergent ferrofluid structures when the radial magnetic field is shifted off-center. Our results show that the symmetry and location of the applied radial magnetic field play a key role in determining the shape and dynamical response of the ferrofluid droplet, with the off-centered radial field leading to asymmetric interfacial patterns that drift away from the magnetic fields center. Our early nonlinear findings indicate that stationary shapes only develop when the fields center is aligned with the center of the Hele-Shaw cell (i.e., with the center of the originally circular ferrofluid drop). We have also found that small misalignments between the center of the droplet and the center of the radial field can induce drastic changes in the pattern formation process, including a strong modification in the number of fingered protrusions formed. The influence of the ferrofluid's magnetic susceptibility, and the impact of random perturbations in the initial conditions are also scrutinized.

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CP26

Master Stability Curves for Travelling Waves

Studying the existence and stability of periodic traveling waves in networks of ordinary differential equations (such as discrete rings and lattices) is a challenging problem to tackle when dealing with a large number of nodes. In this talk, we will present a theoretical and numerical framework for effectively determining the spectrum and stability of such waves in networks with Z_n-equivariance. In this framework, a delay-advance differential equation (master equation) is derived and used to set up a suitable two-point boundary problem (2PBVP) that captures the stability of the wave in the network. Since the defined 2PBVP is independent of the network size, it is suitable for numerical continuation. In this way, we compute a master stability curve containing the spectrum of the traveling wave, which also captures its spectrum when embedded in even larger networks with higher wavenumber. Thanks to this stability curve, instability and multistability in networks can be understood by varying the wave number as a continuous parameter and observing crossings of the master stability curve with the imaginary axis. To showcase our framework, we consider a dissipatively coupled ring of Fitzhugh-Nagumo oscillators and study the coexistence of different attracting traveling waves at different network sizes.

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CP26

Pattern Formation in Soil Organic Carbon Dynamics: Microbial Activity, Chemotaxis and Data-Driven Methods

Modelling Soil Organic Carbon (SOC) dynamics is important for addressing climate change challenges. Sequestering SOC can significantly reduce greenhouse gas emissions and mitigate climate change effects. We will focus on two reaction-diffusion chemotaxis systems for SOC dynamics: the spatial MOMOS [A.Hammoudi, O.Iosifescu, Chinese Annals of Mathematics, Series B (2018)] and the Mimura-Tsujikawa [M.Mimura, T.Tsujikawa, Physica A: Statistical Mechanics and its Applications (1996)] models, both supporting chemotaxis-driven pattern formation. This is important for explaining soil aggregation and the spatial organization of microorganisms. We will use data-driven methods to reproduce patterns and make future predictions. A key advantage of these techniques is their direct application to experimental data. Specifically, we will consider the piecewise Dynamic Mode Decomposition (pDMD) method [A.Alla, A.Monti, I.Sgura, Computers & Mathematics with Applications (2024)]. We will show that the pDMD method is able not only to reproduce the spatial patterns, but also to make future predictions [A.Monti, F.Diele, D.Lacitignola, C.Marangi, arXiv preprint (2024)]. **Acknowledgements.** Funder: Project funded under the NRRP, M4 C2 I1.4 - Call for tender No.3138/2021, Decree n.3175/2021 MUR funded by NextGenerationEU. Award Number:Project code CN00000033, Concession Decree No. 1034/2022 MUR, CUP B83C22002930006, Project title "National Biodiversity Future Center-NBFC".

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CP26

Synchronized Memory-Dependent Intracellular Oscillations in Compartmental-Reaction Diffusion Systems

The Kuramoto model has been used in the last decades to gain insight into the behavior of coupled discrete oscillators, as it is simple enough to be analyzed and exhibits a breadth of possible behaviors, such as synchronization, oscillation quenching, and chaos. However, the question arises how one can derive precise coupling terms between spatially localized oscillators that interact through a time-dependent diffusion field. We focus on a compartmental-reaction diffusion system with nonlinear intracellular kinetics of two species inside each small well-separated cell with reactive boundary conditions. For the case of one-bulk diffusing species in $\mathbb{R}^2$, we derive a new memory-dependent integro-ODE system that characterizes how intracellular oscillations in the collection of cells are coupled through the PDE bulk-diffusion field. By using a "sum-of-exponentials' method to derive a fast time-marching scheme for this nonlocal system, diffusion induced synchrony (in-phase, anti-phase, mixed-mode etc) is examined for various spatial arrangements of cells. This theoretical modeling framework, relevant when spatially localized nonlinear oscillators are coupled through a PDE diffusion field, is distinct from the traditional Kuramoto paradigm for studying oscillator synchronization on networks or graphs. It opens up new avenues for characterizing synchronization phenomena associated with various discrete oscillatory systems in the sciences, such as quorum-sensing behavior.

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CP27

Synchronization in Networked Chaotic Systems Using Switching and Periodic Coupling Strengths

The synchronization problem of networked chaotic systems coupled through time-varying coupling strengths is investigated using two main approaches. To this end, the x-coupled Rssler system is employed as a case study. In the first approach, the coupling strength switches among multiple fixed values, with each value being active for a specific dwell time, where the coupling strength is periodic with a specific period. The effect of period and dwell times on synchronization is studied using the Master Stability Function (MSF). In this approach, the behavior of the networked system is examined under cooperative/competitive interactions, where cooperative interaction corresponds to a positive value of the coupling strength, while competitive interaction corresponds to a negative value. The positive values of the coupling strength can be chosen within or outside the synchronization range, according to the MSF for the static coupling case. In the second approach, the time-varying coupling strength changes periodically according to a sinusoidal function with a specific amplitude and forcing frequency. In this case, synchronization of the coupled system is analyzed with respect to both amplitude and forcing frequency using the MSF. In both approaches, windows of synchronization are observed in the corresponding MSF.

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CP27

Classification of Reduced Lattices of Synchrony Subspaces

We consider a regular coupled cell network and study its lattice of synchrony subspaces. A synchrony subspace corresponds to a partition of cells, which represents synchronized clusters determined solely by its network structure. A lattice represents a hierarchy among all possible synchronized clusters of a network. We developed a computer algorithm which reduces a lattice structure to a simpler form by identifying an equivalent synchrony subspace, which leads to a synchrony-breaking bifurcation analysis. We classify this reduction procedure of a lattice by using the Jordan normal form of the adjacency matrix representing the network structure and assigning a well-defined non-negative integer index to a lattice.

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CP27

Network Optimization for Synchronizing Systems with Physics-Informed AI

Synchronization in networked systems critically depends on network topology. We introduce a physics-informed framework to optimize network structures for enhanced synchrony in oscillator networks. When analytical expressions for the objective function are available, we employ gradient-based optimization of network topology. When only the system dynamics are known, we optimize topology by integrating the dynamics directly into the optimization process. Networks are parameterized either directly through the adjacency matrix or via a learned function mapping node pairs to edge weights. We demonstrate these methods by optimizing synchrony in oscillator networks, showing how each approach tailors topology to enhance coherence. Our results not only improve synchronization but also recapitulate known properties that promote synchrony, validating the effectiveness of our framework. If time permits, we'll discuss complementary methods that do not require explicit knowledge of the system's equations and how this approach can extend to other dynamical processes. Our approach bridges dynamics theory and machine learning, providing powerful tools for designing optimal networks to tune dynamical properties.

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CP27

A Deep Learning and Data-Driven Process Approach for Synchronization in the Hodgkin-Huxley Model

Resonance and synchronized rhythm are significant phenomena observed in dynamical systems in nature, particularly in biological contexts. These phenomena can either enhance or disrupt system functioning. Numerous examples illustrate the necessity for organs within the human body to maintain their rhythmic patterns for proper operation. For instance, in the brain, synchronized or desynchronized electrical activities can contribute to neurodegenerative conditions like Huntington's disease. In this work, we utilize the well-established Hodgkin-Huxley (HH) model, which describes the propagation of action potentials in neurons through conductance-based mechanisms. Employing a "data-driven" approach alongside the outputs of the HH model, we introduce an innovative technique termed Dynamic Entrainment. This technique leverages deep learning methodologies to dynamically sustain the system within its entrainment regime. Our findings show that the results of the Dynamic Entrainment technique matches with the outputs of mechanistic (HH) model.

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CP28

Pulsed Semi-Conductor Power Lasing Using Multiple Tuned Self-Feedback Loops

We consider the problem of generating high power pulses from single and coupled semi-conductor lasers while operating in a continuous lasing mode. Past research has shown that lasers in general, when coupled, prefer to be in an asynchronized state. Recent work on incorporating delayed inter-laser coupling along with self-feedback has demonstrated how a network of lasers can synchronize. Delayed self-feedback networks have been shown to synchronize in semi-conductor lasers as well as ring fiber lasers. Here, we extend this framework to generate large amplitude pulsed laser operation for continuous coupled networks of semi-conductor lasers. We show, in a model of continuous-wave driven lasers, that multiple delay feedback terms are capable of stabilizing highly unstable periodic orbits representing pulse-like behavior with amplitude two orders of magnitude higher than the drive and three orders higher than the threshold, that these pulse-like orbits may be synchronized with delay-coupling to yield linear scaling of the peak amplitude even under heterogeneity of the pump phase, and that these pulse patterns are robust to both additive noise and transient perturbations of the drive. Remarkably, our approach is also shown to stabilize unstable periodic orbits in some other chaotic systems, including in high dimensions.

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CP28

Stabilization of Steady-States in a Three Dimensional Network of Ferromagnetic Nanowires

In this work, we analytically investigate the stability of steady-states in a three-dimensional network of ferromagnetic nanowires. We construct a three-dimensional network nanostructure comprising an array of straight nanowires aligned parallel to each other at an equidistance. The analysis is performed within the classical framework of the Landau-Lifshitz equation. We consider the finite network model consisting of infinite- and finite-length nanowires. For each case, we derive sufficient conditions demonstrating that the steady-states are exponentially stable. We remark that these conditions depend on the damping and anisotropy coefficients and remain unaffected by the overall size of the network and the lengths of the nanowires.

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CP28

Dynamics of Two Optically Coupled Semiconductor Lasers

Coupled semiconductor lasers are systems with intricate dynamics that are of significant interest for a wide range of photonic applications. Extensive previous work has been investigated in the injection-locking architecture with semiconductor lasers which delivers extraordinary physics results. In this work, we conduct bifurcation analysis of a pair of nonidentically pumped diode lasers using MATCONT - a numerical tool useful in bifurcation studies. We find similarities with the optically injected locking laser model providing additional insight into the origin of some of these dynamics. Furthermore, these results prove useful as a test bed for the investigation of limit cycles subjected to quantum noise in systems of two optically coupled quantum oscillators.

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CP28

Controlled Erasure as a Building Block for Universal Thermodynamically-Robust Superconducting Computing

Improving the energy efficiency of computing devices remains a fundamental engineering and social challenge of increasing importance. To help address this challenge, we extend an alternative computing paradigm which manipulates microstate distributions that reside in the metastable minima of a potential energy landscape. These minima serve as mesoscopic memory states, whose dynamic manipulation corresponds to information processing. Central to our results is the control erase (CE) protocol, which controls the landscapes metastable memory states in order to selectively store or erase information. Importantly, successive CE executions can implement the NAND gate—a logically-irreversible universal logic gate. We show how to practically implement a NAND gate with a device created by two inductively-coupled superconducting quantum interference devices (SQUIDs). Using bifurcation theory, we identify circuit parameter ranges which give rise to CEs that are robust against logical errors. These SQUID-based devices are capable of operating above GHz frequencies and at the $k_B T$ energy scale. Further optimized devices and protocols can provide a universal computing substrate that is both computationally fast and energy efficient.

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CP28

Tiny Coupling in Pulse Width Oscillators on Fpgas

We examine a small coupling effect in populations of pulse width oscillators in Field Programmable Gate Arrays (FPGAs). This work studies not one particular oscillator, but instead a small set of oscillators that share the common characteristic of a pulse width state variable engineered to realize a selected discrete, 1-D map (chaotic or otherwise). This set of oscillators is unique because every oscillator in a given population utilizes the exact same physical hardware. Thus, implementation mismatch between oscillators in a population is minimized. Surprisingly, these oscillators exhibit an extremely small coupling effect unanticipated by ideal modeling. The coupling is analyzed in two ways: first, by applying an information theory statistics test to the symbol stream from a population of chaotic pulse width oscillators. Second, through modeling the velocity restitution of the oscillators. These oscillators are appealing for cyber security applications that require an entropy source grounded in first principles theory; hence, understanding the coupling is paramount.

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CP29

The Shape of Sleep: How Timescale Separation Reveals Geometric Structure in a Mathematical Model of the Sleep/wake Cycle

Good sleep is essential for overall health. Yet many people suffer from insufficient sleep or sleep disorders. Even though we do not fully understand why we sleep, mathematical models exist that capture the broad features of sleep-wake regulation and are widely used to model fatigue risk. Most mathematical models do not distinguish between the two main sleep states, rapid eye movement (REM) and non-rapid eye movement (NREM) sleep. An exception is the Behn-Booth model: an 8-dimensional system of differential equations that captures the firing of neuronal groups controlling wake and sleep states. The model also incorporates global aspects of sleep regulation, including a use-dependent homeostatic drive and action of the daily circadian body clock. The Behn-Booth model has been analysed as a two-timescale fast-slow system, which has provided useful insight into the mechanisms that produce different sleep patterns. Here, we study the Behn-Booth model as a three-timescale problem to reveal additional geometric structure that organises oscillations between sleep states. This structure helps us understand the model factors determining the duration of NREM-REM cycles and the relative time spent in each state. This deeper geometric understanding of the generation of NREM-REM cycles brings insight into the relationship between model predicted and observed patterns of NREM-REM cycles and suggests ways in which models could be modified to more accurately reflect human sleep patterns.

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CP29

Mathematical Modeling of the Efficacy of Bright Light Therapy for Circadian Entrainment

Most humans possess the ability to entrain their circadian rhythms to the 24-hour light-dark cycle. However, certain individuals, such as those who suffer from seasonal affective disorder or various forms of depression, are unable to entrain. In other cases, individuals can entrain but at a circadian phase that is misaligned with the 24-hour light-dark cycle. To correct these conditions, patients are prescribed bright light therapy (BLT) where they spend 30 to 60 minutes in the morning in front of a high intensity light box. Empirical results have shown that BLT can be effective in some cases but leave open the explanation for why it works or does not. Here we present a mathematical model that includes the melatonin cycle for the effect of BLT on the circadian rhythm of depressive patients. We show that the efficacy of BLT is dependent on a combination of factors including the time of the day at which BLT is administered, the ability of the individual to transduce light and the individuals endogenous body clock. We employ a combination of analysis of the entrainment map that we have previously developed along with numerical simulations to derive conditions under which entrainment is possible. Our results can be used to suggest strategies for how different individuals can use BLT to achieve entrainment or proper alignment with the 24-hour light-dark cycle.

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CP29

A Minimal Model of Cognition Based on Oscillatory and Current-Based Reinforcement Processes

Building mathematical models of brains is difficult because of the sheer complexity of the problem. One potential starting point is through basal cognition, which gives abstract representation of a range of organisms without central nervous systems, including fungi, slime moulds and bacteria. We propose one such model, demonstrating how a combination of oscillatory and current-based reinforcement processes can be used to couple resources in an efficient manner, mimicking the way these organisms function. A key ingredient in our model, not found in previous basal cognition models, is that we explicitly model oscillations in the number of particles (i.e. the nutrients, chemical signals or similar, which make up the biological system) and the flow of these particles within the modelled organisms. Using this approach, we find that our model builds efficient solutions, provided the environmental oscillations are sufficiently out of phase. We further demonstrate that amplitude differences can promote efficient solutions and that the system is robust to frequency differences. In the context of these findings, we discuss connections between our model and basal cognition in biological systems and slime moulds, in particular, how oscillations might contribute to self-organised problem-solving by these organisms.

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CP29

Theoretical Considerations for Circadian Medicine

What effect sizes should we expect from circadian medicine? With limited data on dosing around the clock, coupled with minimal controls for interindividual variability in the real world, solid insights into how much timing actually matters for medicine can be hard to come by. Yet with computational techniques and mathematical modeling, we can begin to build an intuition for the conditions under which timing should and should not play an important role, as well as how factors such as pharmacokinetics, target availability, and therapeutic window may interact with endogenous rhythms in the body. In this presentation, I will show a theoretical framework for circadian medicine and map simulations derived from this framework to real world drug timing data for temozolomide treatment in glioblastoma.

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CP29

Reservoir Computing with Short-Term Synaptic Plasticity for Goal-Oriented Action Planning

Action planning requires the ability to remember a final goal and decompose it into sequential, immediate objectives. This process is believed to rely on working memory (WM), maintained by recurrent neuronal networks in the prefrontal cortex. In this study, we propose a computational model of action planning based on reservoir computing (RC), motivated by the similarity that RC incorporates a recurrent structure and thus possesses functions that, like the prefrontal cortex, realize WM. To enhance the physiological validity of the proposed model, we introduce reward-based learning and short-term synaptic plasticity (STP). The model's performance was evaluated using a path-planning task that requires short-term memory of the goal position and the generation of multiple sequential actions. Evaluation results confirmed that the model achieves primate-level performance in terms of goal achievement rate and noise robustness. Furthermore, we verified that STP enhances the WM performance achieved by RC, by optimizing information representation within the reservoir. This finding advances our understanding of the dynamic properties of RC models and contributes to elucidating information representation in the brain.

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CP30

Toward An Explanatory Model of Sea Turtle Nesting: Simulating Sea Turtle Nesting Data to Better Understand Decision to Nest

The variability of nest count from one night to the next is well known to sea turtle biologists and conservationists. Indeed, the number of sea turtles that nest on a given beach can vary from the seasonal maximum to zero (and back) on consecutive nights. Such fluctuation poses obvious difficulties for those studying and protecting sea turtles. For beaches that cannot achieve 100% monitoring coverage or that have significant ecotourism components reliant on observing nesting turtles, the capacity to anticipate nights with high nesting activity would be very helpful operationally and financially. An ideal predictor might answer the question: How many turtles are likely to nest tonight? Before approaching that (admittedly aspirational) outcome, we first need to better understand the factors influencing potential nesting synchronicity. Existing studies on nest counts typically have the goal of estimating nesting numbers as a proxy for the total population. (See, for example: Whiting et al, 2014, `doi:10.3354/meps10832`). In the context of estimating total population, it is reasonable to smooth out the internight variability in nest counts. Precisely because of that smoothing, data they simulate do not exhibit the desired variability. In this talk we present preliminary results comparing the capacity to generate realistic internight nest count variability of three variations of a novel, individual-based sea turtle nesting model.

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CP30

Spatial Characterizations of Bacterial Dynamics for Food Safety: Effect of Water Reuse on Dynamics of Campylobacter and E. Coli During Poultry Chilling

Current models of bacterial dynamics in shared water environments often assume uniform mixing profiles. However, given industry specifications, uniform mixing is not always applicable. To address this, we created a reaction-diffusion-advection model tracking changes in water chemistry and bacteria levels in a water compartment. We specify our model forms for poultry chilling, as it features an interplay of bacteria, water chemistry and water flow dynamics and directly influences public health risks linked to poultry consumption. Our model has a unique, globally attracting equilibrium, justifying practical use of the steady-state solution. Water chemistry parameters and E. coli and Campylobacter (Campy) transfer/inactivation rates were determined from commercial data. Post-chill E. coli levels on carcasses were computed and compared to USDA guidelines. Post-chill Campy levels were calculated and compared with the FSIS limit of detection. On average, results show a 1.5 log reduction of E. coli and a 2 log reduction of Campy on carcasses when varying pre-chill levels from 3 to 7 log10 CFU/carcass. Sensitivity analysis reveals two tank regimes: the carcass entry portion, where bacterial levels are controlled by shedding/attachment rates and the carcass exit part of the tank characterized by free chlorine inactivation kinetics. Our model is key for improving pathogen control as well as for establishing spatial models for processing fresh produce and pork products.

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CP31

Energy-Efficient Flocking Without Dissipativity

Modeling collective motion in multi-agent systems has gained significant attention. Of particular interest are sufficient conditions for flocking dynamics. We present a generalization of the multi-agent model of Olfati-Saber [Olfati-Saber, R, IEEE Trans Autom Control 51:401420, 2006] with nonlinear navigational feedback forces. Unlike the original model, ours is not generally dissipative and lacks an obvious Lyapunov function. We address this by proposing a method to prove the existence of an attractor without relying on LaSalles principle. Other contributions are as follows. We prove that, under mild conditions, agents velocities approach the center of mass velocity exponentially, with the distance between the center of mass and the virtual leader being bounded. In the dissipative case, we show existence of a broad class of nonlinear control forces for which the attractor does not contain periodic trajectories, which cannot be ruled out by LaSalles principle. Finally, we conduct a computational investigation of the problem of reducing propulsion energy consumption by selecting appropriate navigational feedback forces.

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CP31

Fast and Slow Clustering Dynamics of Cucker-Smale Ensemble with Internal Oscillatory Phases

We study fast and slow clustering dynamics of Cucker-Smale ensemble with internal phase dynamics via the Cucker-Smale-Kuramoto (in short CSK) model. The CSK model describes the emergent dynamics of flocking particles with phase dynamics. It consists of the Cucker-Smale flocking model and the Kuramoto model, and their interplay is registered in the communication weight function between particles. We present a sufficient framework for mono-cluster flocking and complete synchronization in terms of system parameters and initial data. In particular, the mono-cluster flocking will emerge exponentially fast (fast dynamics). On the other hand, when initial spatial-velocity configuration is close to the bi-cluster flocking, we also provide a sufficient framework leading to convergence of bi-cluster flocking algebraically slow depending on the decay rate of the communication weight (slow flocking dynamics). We also provide several numerical examples and compare them with analytical results.

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CP31

Macroscopic Performance Effects of Micro and Meso-Scale Heterogeneities in Traffic Flow

Via mathematical models and the systematic transition across scales, it is established how vehicle (micro) and traffic waves (meso) scale features of traffic flow manifest in the system-level (macro) performance of vehicular traffic flow, like road throughput and the energy footprint of traffic. The mathematical analysis of dynamical models is complemented by simulations and the study of real-world traffic data found via a series of field studies, including a 100-control vehicle experiment conducted by the CIRCLES consortium.

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CP31

Low-Dimensional Modelling of Swarming Behavior Using Proper Orthogonal Decomposition and Spectral Proper Orthogonal Decomposition

We present a method for constructing Reduced Order Models (ROM) for large systems of coupled agents forming self-organized patterns. This method is based on proper-orthogonal decomposition (POD) or on spectral proper orthogonal decomposition (SPOD), applied to the main patterns exhibited by a system of N=150 communicating agents. By combining just a few modes of the ring pattern and rotating pattern of the swarming system we obtain a low dimensional model which exhibits the same patterns over a significant range of coupling strength and communication delay values. This method replaces solving a large system of coupled delay-differential equations, given by the law of motion of individual agents, with solving just a few delay differential equations for the reduced system. Using this ROM we recommend data collection strategies in parameter space, for updating the POD modes (SPOD modes), so that a larger parameter space ca be captured by the reduced model. In this way, application of swarming algorithms in real experiments can be facilitated, while retaining the behavior of the original system at desired parameter values.

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CP31

Optimal Routing of Multi-Agent Swarms Via Low-Dimensional Approximation

Swarming models can demonstrate patterns similar to those seen in schools of fish or flocks of birds, human crowds, and swarms of robots moving together. Here we assume agents in the swarm know about the locations and velocities of nearby agents but may not have a complete picture of the geometry and dynamics of the swarm as a whole. A key question we investigate is how can one navigate the swarm through a landscape with obstacles. We present a method for approximating a swarm of agents macroscopically and navigating this macroscopic swarm through a landscape using optimal control. Then we present how one may add dynamics to the microscopic swarming model to allow the swarm to follow the computed path well attempting to minimize the deformation done to the swarm at a large scale.

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MS0

Icebreaker Session

All Participants
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MS1

Instabilities and Mixing

Interfaces and interfacial mixing and their non-equilibrium dynamics control a broad range of processes in nature, technology, industry, from supernovae and fusion to alternative energy sources and purification of water. Mathematically, these problems are extremely challenging to study in theory and in simulations. Analytically, one needs to solve the conservation laws, augmented with singular boundary value problem and ill-posed initial value problem. Numerical modeling imposes high demands on the accuracy, precision and the scale of computations. The mini-symposium builds upon recent achievements in understanding the dynamics of interfaces and mixing, and reports solutions for long-time challenges in fundamentals and applications.

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MS1

Vortex Reversal As a Precursor of Bacterial Turbulence

Active turbulence, or chaotic self-organized collective motion, is often observed in concentrated suspensions of motile bacteria and other systems of self-propelled interacting agents. To date, there is no fundamental understanding of how geometrical confinement orchestrates active turbulence and alters its physical properties. By combining large-scale experiments, computer modeling, and analytical theory, we have discovered a generic sequence of transitions occurring in bacterial suspensions confined in cylindrical wells of varying radii. With increasing the well's radius, we observed that persistent vortex motion gives way to periodic vortex reversals, four-vortex pulsations, and then well-developed active turbulence. Using computational modeling and analytical theory, we have shown that vortex reversal results from the nonlinear interaction of the first three azimuthal modes that become unstable with the radius increase. The analytical results account for our key experimental findings. To further validate our approach, we reconstructed equations of motion from experimental data. Our findings shed light on the universal properties of confined bacterial active matter and can be applied to various biological and synthetic active systems.

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MS1

Traveling Fluid Fronts into Closing Gaps: Second-Kind Self-Similar Solutions of Non-Standard Degenerate Diffusion Equations

Self-similar solutions of the second kind arise during the spreading and leveling of gravity current in a variable-width Hele-Shaw cell. These traveling fluid fronts are understood by transforming the governing PDE into a nonlinear ODE. Traditionally, integral curves between certain fixed points in such a phase plane reveal the self-similar solutions. Although convenient, this phase plane formalism does not allow for the determination of a scaling constant related to the value of the self-similar variable at the moving front. In previous work, this constant was fit from numerical simulations of the governing partial differential equation from lubrication theory and/or experiments. Instead, we show how to reveal both the self-similar solutions and pre-factors by studying the far-field behavior and self-similar asymptotics for the governing non-standard nonlinear degenerate diffusion equations (non-standard in the sense that the PDE does not feature the usual n-dimensional div-grad, or Laplace-type, operator).

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MS1

Analysis and Computation of Models of Moire-Regulated Metal Nanocluster Self-Assembly

Bilayer graphene with a top layer rotated with respect to a bottom one typically forms a periodically corrugated surface called a Moiré superlattice. This surface presents a complex potential energy landscape for diffusion of deposited atoms or molecules, which can be exploited to assemble nanoclusters with well-defined positions and sizes. We analytically constructed Moiré superlattices and corresponding potentials for various values of a twist angle and strain, and followed with a formulation of a nonlinear diffusion equation for continuous submonolayer adsorbate coverage field $\rho(x, y, t)$. Next, we analytically determined a quasi-2D steady-state solution $\rho(x, y)$, computed solutions of a full 2D nonlinear diffusion problem for single-metal adsorbate, and determined the kinetics of approaching a steady-state. As the alternative and complimentary approach, we formulated a Langevin equation for diffusion of individual atoms on a Moiré and used GPU-accelerated computations to determine the statistics of diffusion for various random initial configurations of atoms. We also determined stable final nanocluster configurations of N atoms using these computations and a graph-theoretical approach. Finally, we formulated a simple diffusion-type model for Moiré-regulated composition of bimetallic nanoclusters and computed its kinetics for several combinations of adsorption potentials and their relative strengths.

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MS2

Comparison of Systems Using Koopman Operator Methods

Computationally efficient solutions for pseudometrics quantifying deviation from topological conjugacy between dynamical systems are presented. Deviation from conjugacy is quantified in a Pareto optimal sense that accounts for spectral properties of Koopman operators as well as trajectory geometry. Theoretical justification is provided for computing such pseudometrics in Koopman eigenfunction space rather than observable space. Furthermore, it is shown that theoretical consistency with topological conjugacy can be maintained when restricting the search for optimal transformations between systems to the unitary group. Therefore the pseudometrics are based on analytical solutions for unitary transformations in Koopman eigenfunction space. Geometric considerations for the deviation from conjugacy Pareto optimality problem are used to develop scalar pseudometrics that account for all possible optimal solutions given just two Pareto points. The approach is demonstrated on two example problems; the first being a simple benchmarking problem and the second an engineering example comparing the dynamics of morphological computation of biological nonlinear muscle actuators to simplified mad-made (including bioinspired) approaches. The benefits of considering operator and trajectory geometry based dissimilarity measures in a unified and consistent formalism is demonstrated.

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MS2

Effects of Internal Resonance and Damping on Koopman Modes

This study investigates the nonlinear normal modes (NNMs) of a systemcomprisingof twocoupled Duffingoscillators,with one oscillatorbeing grounded and with the coupling being both linear and nonlinear. The study utilizesthe eigenfunctions of the Koopman operator and validates their connection with the ShawPiere invariant manifold framework for NNMs. Furthermore, the study delves into the impact of internal resonance and dissipation on the accuracy of this framework by defining a continuous quantitative measure for internal resonance. The applicability and robustness of the framework for the systems which are very similar qualitatively to that of an ENO, are also observed and discussed about the limitations of the approximation technique.

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MS2

Computational Algebra of Koopman Eigenfunctions

If the flow map of a dynamical system is invertible, the eigenfunctions of the Koopman operator of the system form a group. In this contribution, we employ this property to speed up the numerical computation of the eigenspaces of the operator. Given a small set of eigenfunctions that are approximated conventionally, we construct polynomials of these eigenfunctions to obtain a much larger set. For nonlinear systems with simple attractors such as steady states and limit cycles, we discuss the construction of eigenfunctions across these singularities.

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MS3

Rate and Bifurcation Tipping in Asymptotically Slow-Fast Systems

In this talk, we consider a geometric approach to the study of bifurcation and rate induced transitions in a class of *asymptotically slow-fast systems*, which are in some sense intermediate between the (smaller resp. larger) classes of asymptotically autonomous and non-autonomous systems. After showing that the relevant systems can be viewed as singular perturbations of a limiting system with a discontinuity in time, we consider an analytical framework for their analysis based on geometric blow-up techniques. Using this approach, we provide sufficient conditions for the occurrence of bifurcation and rate induced transitions in low dimensions, as well as sufficient conditions for tracking in arbitrary (finite) dimensions, i.e. the persistence of an attracting and normally hyperbolic manifold through the transitionary regime. The proofs rely on geometric blow-up, a variant of the Melnikov method which applies on non-compact domains, and general invariant manifold theory. We conclude by applying these results to a low-dimensional problem with forward and backward attractors that feature slow but non-constant dependence on time.

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MS3

Resonance in Rate-Induced Tipping Due to Timescale Variation of Chaotic Forcing

Many physical systems are forced by external factors which are subject to chaotic variation. A particular example is in applications to weather and climate where chaotic behaviour is prevalent across timescales. If the system in question has multiple attracting solutions under the bounds of variation, then partial tipping can be observed. This is where, initialising from the base attractor, only a subset of realisations undergo a transition to an alternative attractor. We explore this phenomenon in a low-order model of ice-age dynamics. The model exhibits bistability between two equilibria in one bistable region of the parameter space, and between an equilibrium and a periodic orbit in another bistable region. When allowing for chaotic variation of the parameters within these bistable regions, the solution can undergo either reversible or irreversible tipping between attractors. We find that the timescale of the chaotic variation induces resonance-like behaviour in that there exists an optimal timescale for tipping as well as a minimum timescale for the occurrence of tipping. We also explore the crossing of the stable manifold of the time-varying saddle equilibrium through the use of finite-time Lyapunov exponents.

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MS3

Tipping Mechanisms in a Carbon Cycle Model

Rate-induced tipping (R-tipping) occurs when a ramp parameter changes rapidly enough to cause the system to tip between co-existing, attracting states, while noise-induced tipping (N-tipping) occurs when there are random transitions between two attractors of the underlying deterministic system. This work investigates R-tipping and N-tipping events in a carbonate system in the upper ocean, in which the key objective is understanding how the system undergoes tipping away from a stable fixed point in a bistable regime. While R-tipping away from the fixed point is relatively straightforward, N-tipping poses challenges due to a periodic orbit forming the basin boundary for the attracting fixed point of the underlying deterministic system. We compute the most probable escape path for our system, resulting in a firm grasp on the least action path in an asymmetric system of higher scale. Our analysis shows that the carbon cycle model is susceptible to both tipping mechanisms when using the standard formulations, and we discuss what this means in the context of the physical application.

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MS3

On Rate-Induced Tipping: Thresholds, Edge States and Base States

In this talk I will introduce and give an overview of rate-induced tipping (R-tipping) in nonlinear systems with time-varying inputs - a true non-autonomous instability that may, but usually does not involve the passage through a classical autonomous bifurcation. I will describe the approach chosen for the analysis of non-autonomous dynamical systems and a special compactification technique that allows to give rigorous conditions for the occurrence of R-tipping. Furthermore, I will describe the concepts of base states from which the system R-tips, thresholds and quasithresholds that are crossed in the process of R-tipping, and non-attracting edge states to which the system converges for special critical input rates. I will highlight the challenges associated with quasithresholds in multiple timescale (fast-slow) systems and illustrate these concepts with examples from ecosystems and zombie fires.

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MS4

Principles of Efficient Resource Exchange Dynamics in Honeybee Colonies

We develop and analyze a velocity-jump process model of honeybee movement with socially informed reorientation rules. The colony can be tasked with having the motile "empty" bees obtain food from "full" bees who may either be stationary or motile. Analysis of the model reveals ranges of reorientation and exchange parameters that lead to efficient resource exchange, which we can identify in limiting cases using asymptotics for extremal first passage time problems. Our results contribute new insights into optimal transport on stochastic and motile networks through perturbations about mean field limits of a well mixed group.

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MS4

Individual-Level Social Network Models of Substance Use Disorders

Substance use disorder is a complex condition that leads to problematic drug use despite adverse consequences to ones health and social functioning. Unlike pathogenic disease which spreads solely through contact between individuals, the mechanisms behind the development of use disorders are fundamentally different. Our work takes an individual-level approach by using cellular automata on social networks to model opioid and alcohol use disorders (OUD and AUD, respectively). First, we investigate the relative influence of a network-based social contagion on the spread of prescription and illicit opioids by fitting a stochastic cellular automata model to a data-driven differential equations model, finding those with prescription-based OUD and connections to illicit heroin or fentanyl users must quickly transition to using illicit opioids themselves to replicate known population dynamics. Second, we extend this framework to an application in AUD where we additionally stratify susceptibility by assuming that individuals are more likely to engage in problematic drinking behaviors if they lack strong social support. We found that AUD outcomes are made worse when networks have higher levels of isolation even when the average number of social connections per agent is constant. Taken together, our work illustrates the importance of including individual variation in models of noninfectious disease.

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MS4

Planktos: An Agent-Based Modeling Framework for Collective Behavior in Fluid Flow Around Immersed Structures

This talk will focus on an introduction to the features, methods, and applications of the *Planktos* toolkit, an agent-based modeling framework for studying the collective behavior of small organisms (self-propelled particles) within fluid flow around immersed structures. This framework is robust to both 2D and 3D applications, time-varying fluid flow, and a wide range of dynamical systems models. Recent work includes the addition of moving immersed boundary structures and additional tools for analyzing the biological implications for active particles within a structured background flow.

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MS4

Data Assimilation and Model Selection for Collective Motion in Locust Swarms

In a striking example of collective behavior, swarms of locusts march in an aparently coordinated direction. Various swarm morphologies emerge in these groups that aid in feeding or migration, depending on the environment through which the swarm moves. However, unlike eusocial insects (such bees or ants) locusts have no social structure (or queen) to facilitate this directed motion. Instead, agent-based models with identical individuals are anatural lense with which to study the collective motion of locusts. In this talk, we will introduce a framework for evaluating the appropriateness of several models for individual interaction. The work is made possible by recent advances in the availability and magnitude of trajectory data on individual locusts within a swarm. We formulate a Bayesian particle filter to estimate parameters of a given model for individual interaction based on these data. We next conduct a simulation study using the given model with parameters from the posterior distribution. Finally, we compare quantities aggregated from the simulated data and the empirical data to determine if the model recreates similar collective motion.

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MS5

Learning Linear Response Factors for Computing Transport Coefficients

An important problem in molecular dynamics is the computation of transport coefficients which relate the strength of an external force to the average of an observable. Two commonly used methods for such computations the NEMD method and the Green-Kubo method both suffer from very high variance. Alternatively, one could in principle compute transport coefficients for any observable with sample from the equilibrium distribution using the so-called "linear response factor." However, this linear response factor is typically the solution to PDE in very high dimensions thus rendering standard numerical methods intractable. We present some recent work using neural networks to learn this linear response factor. This function is also the solution to a variational problem involving the equilibrium measure which we use as a training loss. The resulting Deep Ritz loss works better in our numerical experiments compared to PINN losses. We further build into our neural networks the permutation invariance one would expect from particle system. We present the results of numerical studies on harmonically interacting particles as well as particle systems with more realistic interaction potentials.

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MS5

Learning Vector Fields of Differential Equations on Manifolds

I will present an operator-valued kernel to represent vector fields of ordinary differential equations (ODEs) on manifolds. The construction of the kernel imposes the geometric constraints estimated from the data and ensures the computational feasibility for learning high dimensional systems of ODEs. Given the estimated vector fields, we will approximate the exponential maps corresponding to the ODE solution by a novel ODE solver that guarantees the prediction to lie on the manifold in the limit of large data. I will briefly present the theoretical error bound for the proposed solver and numerically demonstrate the effectiveness of the proposed approach on high-dimensional dynamical systems, including the cavity flow problem, the beating and traveling waves in Kuramoto-Sivashinsky equations, and the reaction-diffusion dynamics.

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MS5

Score-Based Generative Models Are Provably Robust and Can Learn Structural Constraints: a Uq Perspective

We demonstrate that score-based generative models (SGMs) are provably robust to practical, multi-sourced errors through a Wasserstein uncertainty propagation theorem, which quantifies how score function errors propagate within a Wasserstein-1 ball around the true distribution under Fokker-Planck dynamics. This theorem leverages Bernstein estimates for Hamilton-Jacobi-Bellman (HJB) partial differential equations, ensuring robustness via the regularizing effects of stochastic diffusion processes and extending to integral probability metrics such as total variation distance and maximum mean discrepancy. The role of symmetrya feature common in data from physics, molecular simulations, and imagesis critical in improving the robustness of SGMs. Using HJB theory, we demonstrate the inductive bias of learning group-invariant distributions and rigorously show that one can learn their score using equivariant vector fields without data augmentation. By incorporating equivariant structures into score parametrization, we quantifiably enhance robustness and reduce approximation error, establishing equivariant design as essential for optimal SGM performance. Our results provide improved, structure-enhanced, sample complexity and Wasserstein generalization bounds for group-invariant target distributions.

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MS5

Goal-Oriented Learning of Ergodic Diffusions Using Error Bounds on Path-Based Observables

In physical systems governed by stochastic differential equations (SDEs), the drift function of the SDE often involves expensive calculations which render numerical simulation to be cost-prohibitive. Our goal in surrogate modeling for SDEs is to learn an approximate drift function such that the surrogate process replicates observables of the system, such as statistics over the path measure of the stochastic process, at a fraction of the cost. We propose a *goal-oriented loss function* for the statistical learning of SDE models which takes the form of an information-theoretic variational bound on the weak error in an observable functional of the process. First, we prove that the weak error in path-based observables can be upper bounded by a term which depends on second moment information of the observable functional and the Kullback-Leibler (KL) divergence between path measures, which is computable using Girsanovs theorem and the relationship between pathwise KL divergence and relative entropy rate. Second, we derive a closed form gradient of the goal-oriented loss function relying on Frechet derivatives to use in gradient descent schemes for the regression task. In numerical studies, we demonstrate that model learning using the goal-oriented loss function can lead to faster convergence to solutions which control error in the observable statistic, in contrast to standard score-based loss functions for learning SDEs.

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MS6

Identifiability Analyses of Multiscale

Uncertainty in parameter estimates from fitting within-host models to empirical data limits the models ability to uncover mechanisms of infection, disease progression, and to guide pharmaceutical interventions. Understanding the effect of model structure and data availability on model predictions is important for informing model development and experimental design. To address sources of uncertainty in parameter estimation, we use four mathematical models of influenza A infection with increased degrees of biological realism. We test the ability of each model to reveal its parameters in the presence of unlimited data by performing structural identifiability analyses. We then refine the results by predicting practical identifiability of parameters under daily influenza A virus titers alone or together with daily adaptive immune cell data. Using these approaches, we present insight into the sources of uncertainty in parameter estimation and provide guidelines for the types of model assumptions, optimal experimental design, and biological information needed for improved predictions.

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MS6

An SIRV Model Considering Imperfect Vaccines and Non-Pharmaceutical Interventions

In this presentation, we propose an extended classical SIRSV model incorporating a vaccinated compartment accounting for an imperfect vaccine with waning efficacy over time. The SIRSV model divides the population into four compartments and introduces periodic re-vaccination with waning immunity. We develop a partial differential equation (PDE) model for the continuous vaccination time and a coupled ordinary differential equation (ODE) system when discretizing the vaccination period. Furthermore, we explore an optimization framework where vaccination rate, re-vaccination time, and non-pharmaceutical interventions (NPIs) can be used as control variables to minimize infection levels. The optimization objective is defined using different norm-based measures of infected individuals. Using path-following techniques in the MATLAB-based COCO platform, we perform a numerical investigation of the dynamical response of the model under varied control parameters, assessing the effects of vaccination and contact restrictions.

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MS6

Assessing the Impact of the Wolbachia-Based Control of Malaria

Malaria remains a significant infectious disease globally, causing hundreds of thousands of deaths each year. Traditional control methods, such as disease surveillance and mosquito control, along with the development of malaria vaccines, have made strides in reducing the disease's impact, but new control methods are urgently needed. *Wolbachia* is a natural bacterium that can infect mosquitoes and reduce their ability to transmit diseases. While initially used to control dengue fever, recent research explored its potential for malaria control. In this study, we develop and analyze a novel mathematical model to assess the potential use of *Wolbachia*-based strategies for malaria control. The model describes the complex *Wolbachia* transmission dynamics among mosquitoes and incorporates key features of malaria transmission in humans with dynamical immunity feedback. We derive the basic reproduction number of the malaria disease transmission, which depends on the prevalence of *Wolbachia* in mosquitoes. Our findings reveal bifurcations in both *Wolbachia* transmission among mosquitoes and malaria transmission in humans, suggesting the potential for malaria elimination through *Wolbachia*-based interventions.

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MS6

Modeling Insecticide Resistance and Management of Malaria Mosquitoes

With over 700,000 annual deaths across the globe due to mosquito-borne diseases, insecticide resistance is a major public health concern. Insecticide-resistant mosquitoes experience both positive and negative selective forces, depending on the resistance genotype, the type and dosage of insecticide applied, and the fitness costs associated with the resistance mutations they carry. Understanding how these forces interact with each other is critical in determining optimal resistance management strategies. We develop and analyze an ODE-based model to examine the impact of various resistance management strategies on the evolution of insecticide resistance in mosquito populations.

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MS7

Generation and Robustness of Rhythmic Patterns in Stick Insect Locomotion

Stick insect locomotion is a valuable model for studying rhythm generation and control due to its experimental accessibility and variety of stepping patterns. This talk focuses on the metathoracic segments of the stick insect's middle leg, modeled by a central pattern generator (CPG) and antagonistic motoneuron (MN) pairs. Using an 18-dimensional system of coupled ODEs, we aim to: i) to identify the dynamic mechanisms capable of generating specific stepping rhythms in three-segment stick insect limb models; (ii) to investigate and explain the robustness and tunability of these outputs, based on parameter changes; and (iii) to analyze how these outputs are coordinated across limb segments. Addressing these objectives will contribute insights not only about insect locomotion but also about other rhythm-generating neuronal networks.

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MS7

How the Spinal Cord Generates Rhythmic Movement and Stops It Again

How does a cat gracefully walk and suddenly freeze when spotting a mouse? So far, it has been difficult to contemplate a neuronal network capable of both autonomous generation of movement and pausing that movement at any point. To better understand the generation and pausing of rhythmic motor activity, we use multi-electrode probes (Neuropixels) in the rat spinal cord during voluntary locomotion. To control the pausing of movement, we utilize optogenetic perturbation and stimulation of the pedunculopontine nucleus, a known regulator of movement arrest. We find that during locomotion, the neuronal manifold activity exhibits robust rotational patterns invariant to speed (Linden, Nature 2022). Further, this trajectory converges to a stable point-attractor precisely at the moment of arrest, where it persists until the movement is resumed. Through computational modeling, we argue that the network is a Continuous Attractor Network, as seen elsewhere in the nervous system (Gardner, Nature 2022), and suggest a structural mechanism of physical implementation.

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MS7

Mechanisms of Robust and Flexible Control of Bursting Activity in Leech Heart Interneurons by Neuromodulation

Neuromodulation adjusts neuronal dynamics to suit behavioral. How it coordinates changes of multiple currents to make the CPGs producing adjustable and robust patterns is an open question. The CPG, controlling the leech heartbeat, is driven by two pairs of mutually inhibitory heart interneurons, HNs, forming half-center oscillators, HCOs. Neuromodulator myomodulin speeds up the HCOs by decreasing Na/K pump current (Ipump) and increasing h-current, navigating between dysfunctional regimes, seizure-like regimes and asymmetric bursting [Ellingson, et al. 2021 J Neurosci 41: 6468-6483] leading to co-existance with a new functional bursting, HFB. HFB has the two times higher spike frequency, while the periods of the coexisting regimes are roughly the same. Here, we show that HFB is supported by the mechanism based on the interaction of the Ipump and Na currents, creating relaxation oscillator dynamics such that: the increase of Ipump speeds up the cycle period by shortening both burst duration and interburst interval [Erazo-Toscano, et al. 2023 eNeuro 10: 119]. This feature contrasts with experimental trends where myomodulin speeds up the period alongside a decrease in Ipump [Tobin, Calabrese 2005 J Neurophys 94: 3938-3950] and resolves the paradox of speeding up the rhythm by monensin upregulating Ipump [Kueh, et al. 2016 eLife 5: e19322]: the transition between the bursting regimes due to neuromodulation can enhance the flexibility and robustness of rhythm adjustments.

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MS7

Attractor-Based Models for Sequences and Pattern Generation in Neural Circuits

Neural circuits in the brain perform a variety of essential functions, including input classification, pattern completion, and the generation of rhythms and oscillations that support functions like breathing and locomotion. There is also substantial evidence that the brain encodes memories and processes information via sequences of neural activity. Traditionally, rhythmic activity and pattern generation have been modeled using coupled oscillators, whereas input classification and pattern completion have been modeled using attractor neural networks. In this talk, I will present models for several different neural functions using threshold-linear networks. Our goal is to develop a unified modeling framework around attractor-based models. The models presented include: a counter network that can count the number of external inputs it receives, encoded as a sequence of fixed points; a model for locomotion that encodes five different quadruped gaits as limit cycles; and a model that connects the sequence of fixed points in the counter network with the attractors of the locomotion network to obtain a new network that steps through a sequence of locomotive gaits. I will also introduce a general architecture for layering networks which produces fusion attractors by minimizing interference between the attractors of individual layers.

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MS8

Fast-Slow and Bifurcation Analysis in Realistic Cardiomyocyte Models

Early Afterdepolarizations (EADs) are abnormal behaviors that can lead to cardiac failure and even cardiac death. In this presentation, we investigate mathematically the occurrence and development of these phenomena in two realistic ventricular myocyte models: the Sato (2009), rabbit, and the O'Hara (2011), human, models. We connect the results with a reduced low dimensional Luo-Rudy cardiac model. By examining the bifurcation structure of the model, we elucidate the dynamical elements associated with these patterns and their transitions. Using a fast-slow analysis, we explore the emergence and evolution of EADs in the low dimensional model and we develop new methodologies for the fast-slow decomposition for the high-dimensional realistic O'Hara model. This is a joint work with J.A. Jover-Galtier, H. Kitajima, M.A. Martinez, S. Serrano, T. Yazawa.

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MS8

Complex Cardiac Excitation Patterns: Superscrolls and Superfilaments in 4D Excitable Media

Each heartbeat is initiated by an excitation wave that propagates through cardiac tissue due to complex electrophysiological processes. Under pathological conditions, such as tachycardia and fibrillation, these spatiotemporal excitation patterns can take on intricate and abnormal forms. A valuable approach to modeling the onset and progression of these patterns is through scroll waves, which can be studied by analyzing their filaments. In this work, we extend the concept of scroll waves to higher dimensions, introducing ”superscrolls” and ”superfilaments.” We demonstrate that the dynamics of superfilaments are influenced by their curvature and by the properties of the excitable medium. These findings have broad implications, extending beyond cardiac systems to general excitable networks, such as neural circuits and rumor propagation in social networks.

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MS8

Optimal Phase-Based Control of Strongly Perturbed Limit Cycle Oscillators Using Phase Reduction Techniques

Phase reduction is a well-established technique for analysis and control of weakly perturbed limit cycle oscillators. However, its accuracy is diminished in a strongly perturbed setting where information about the amplitude dynamics must also be considered. In this work, we consider phase-based control of general limit cycle oscillators in both weakly and strongly perturbed regimes. For use at the strongly perturbed end of the continuum, we propose a strategy for optimal phase control of general limit cycle oscillators that uses an adaptive phase-amplitude reduced order model in conjunction with dynamic programming. This strategy can accommodate large-magnitude inputs at the expense of requiring additional dimensions in the reduced-order equations, thereby increasing the computational complexity. We apply this strategy to two biologically motivated prototype problems and provide direct comparisons to two related phase-based control algorithms. In situations where other commonly used strategies fail due to the application of large-magnitude inputs, the adaptive phase-amplitude reduction provides a viable reduced-order model while still yielding a computationally tractable control problem. These results highlight the need for discernment in reduced-order model selection for limit cycle oscillators to balance the trade-off between accuracy and dimensionality.

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MS8

Spiral Wave Teleportation and Defibrillation through Phase Space Perturbations

The spatiotemporal dynamics of excitable systems can be characterized in phase space, in which their evolution is uniquely defined at every point. For systems capable of sustaining action potentials, such as Belousov-Zhabotinsky (BZ) chemical reactions, the brain, and the heart, the waves action potentials manifest in phase space as a limit cycle that is associated with each points unique phase, or location in the action potential. The tip of the spiral wave is defined as a singularity in this space. Recent simulations and experiments in the BZ reaction have demonstrated that applying a small stimulus across the refractory wave back of the action potential allows for the instantaneous “teleportation of the spiral waves across space, enabling control and termination of the spiral waves. Building on this concept, we have extended it to include perturbations at any point in the action potential limit cycle. This approach could allow for the termination of spiral waves (e.g. defibrillation in the heart) at any moment, provided an appropriate size and strength for the perturbation in phase space. In this talk we present results that examine the relationship between the strength and size of perturbations in relation to the specific phase in the limit cycle at which they are applied. To run these simulations, we used the FitzHugh-Nagumo model and other cardiac models.

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MS9

Finite-Time Lyapunov Exponents for SPDEs with Fractional Noise

We estimate the finite-time Lyapunov exponents for a stochastic partial differential equation driven by a fractional Brownian motion (fbm) with Hurst index $H \in (0, 1)$ close to a bifurcation of pitchfork type. We characterize regions depending on the distance from bifurcation, the Hurst parameter of the fbm and the noise strength where finite-time Lyapunov exponents are positive and thus indicate a change of stability. We discuss this technique for the stochastic Allen-Cahn and Burgers equations. The results on finite-time Lyapunov exponents are novel also for SDEs perturbed by fractional noise.

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MS9

Flowing Through Scales in 2D Stochastic Heat Equations

The stochastic heat equation is a fundamental model in statistical physics featuring noise scaled by the solution itself. In this talk, I will discuss statistics of nonlinear stochastic heat equations in the critical dimension two. Through a renormalization group analysis, these are tied to forward-backward SDEs and quasilinear but deterministic heat equations. This is joint work with Alex Dunlap.

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MS9

Existence of Stationary Measures for SDEs with Generic, Euler-Type Nonlinearities

Many physical phenomena involve the nonlinear, conservative transfer of energy from weakly damped degrees of freedom driven by an external force to other modes that are more strongly damped. For example, in hydrodynamic turbulence, energy enters the system primarily at large spatial scales, but at high Reynolds number, dissipative effects are only significant at very high frequencies. In this talk, I will discuss nonlinear energy transfer and the existence of invariant measures for a class of degenerately forced SDEs on R^d with a bilinear nonlinearity $B(x, x)$ constrained to possess various properties common to finite-dimensional fluid models and a linear damping term $-Ax$ that acts only on a proper subset of the phase space. Existence of an invariant measure is straightforward if $ker A = \{0\}$, but when the kerA is nontrivial, an invariant measure can exist only if the nonlinearity transfers enough energy from the undamped modes to the damped modes. We develop a set of sufficient dynamical conditions on B that guarantees the existence of an invariant measure and prove that they hold “generically within our constraint class of nonlinearities provided that $dim(ker A) < 2d/3$ and the stochastic forcing acts directly on at least two degrees of freedom.

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MS10

Computation and Control of Unstable Steady States for Mean Field Multiagent Systems

In this talk we study interacting particle systems driven by noise, modeling phenomena such as opinion dynamics. We are interested in systems that exhibit phase transitions i.e. non-uniqueness of stationary states for the corresponding McKean-Vlasov PDE, in the mean field limit. We develop an efficient numerical scheme for identifying all steady states (stable and unstable) of the mean field McKean-Vlasov PDE, based on a spectral Galerkin approximation combined with a deflated Newton's method to handle the multiplicity of solutions. Having found all equilibra, we formulate an optimal control strategy for steering the dynamics towards a chosen unstable steady state. The control is computed using iterated open-loop solvers in a receding horizon fashion. We demonstrate the effectiveness of the proposed steady state computation and stabilization methodology on several examples, including the noisy Hegselmann-Krause model for opinion dynamics and the Haken-Kelso-Bunz model from biophysics. The numerical experiments demonstrate the approach can capture the rich self-organization landscape of these systems and stabilize unstable configurations of interest. The proposed computational framework opens up new possibilities for understanding and controlling the collective behavior of noise-driven interacting particle systems, with potential applications in various fields such as social dynamics, biological synchronization, and collective behavior in physical and social systems.

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MS10

A Continuum Mixture of Leaders and Followers: Enhanced Flexibility and Robustness under Behavioral Plasticity Regimes

Behavioral plasticity is the biological mechanism that enables individuals within a group to switch roles in response to a common task. This phenomenon is observed across various animal species, such as in schools of fish or flocks of pigeons, where individuals alternate between leading and following while shoaling to avoid predators or performing homing maneuvers. In such cases, leading the group is not solely a DNA-encoded trait of specific individuals, but it can arise from temporary states, such as acquiring new information about food sources or being positioned at the edge of the formation. In this talk, I present a continuum model for large-scale populations of agents solving a density control task while undergoing behavioral plasticity. Our approach draws inspiration from reacting mixtures, modeling leaders and followers as phases of two interacting fluids, where the reaction represents the plasticity mechanism, allowing for the transformation between leaders and followers. We derive necessary and sufficient conditions for the existence of desired solutions, address their stability properties, and observe that behavioral plasticity enhances flexibility and robustness. This highlights the potential for incorporating plasticity into novel control strategies for large swarms of artificial agents, promoting the emergence of swarm intelligence.

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MS10

Mean-Field Optimal Control with Transient Leadership

We study the control of a system of multi-population agents, described by their spatial position and their probability of belonging to a certain population. The dynamics in the control problem is characterized by the presence of an activation function which tunes the control on each agent according to the membership to a population, which, in turn, evolves according to a Markov-type jump process. In this way, a hypothetical policy maker can select a restricted pool of agents to act upon based, for instance, on their time-dependent influence on the rest of the population. We study a finite-particle control problem and its mean-field limit, identified via Gamma-convergence, ensuring convergence of optimal controls. We discover that the dynamics of the mean-field optimal control is governed by a continuity-type equation without diffusion. We conclude by showing specific applications in the context of opinion dynamics, together with some numerical experiments.

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MS10

Computing Slow Invariant Manifolds with Physics Informed Neural Networks: Applications to Singularly Perturbed and General Fast/Slow Dynamical Systems

Complex dynamical systems frequently exhibit multi-scale behavior, giving rise to emergent behaviors that evolve on low dimensional subspaces. In the presence of multiple timescales, the emergent dynamics is constrained to evolve onto slow invariant manifolds (SIMs), which are crucial for physical understanding and construction of reduced order models (ROMs). In this contribution, we present a physics informed neural network (PINN) approach for computing SIMs in an explicit form, thus facilitating the construction and numerical integration of ROMs. Our approach is based on the solution of the invariance equation (IE) within the framework of Geometric Singular Perturbation Theory (GSPT). We first present our approach for singularly perturbed systems, i.e., systems where the timescale splitting is expressed by a small parameter ϵ. However, real world dynamical systems cannot be easily written in this form and thus, we further extend the approach for general fast/slow dynamical systems. We demonstrate through various stiff benchmark problems that our approach (i) is able to handle emergent behaviors leading to fixed points, limit cycles, but also degenerating ones, (ii) provides SIM approximations of higher accuracy than well-known GSPT techniques, such as the Quasi Steady-State Approximation and the Computational Singular Perturbation, and (iii) is not affected by the magnitude of time-scale splitting, nor the boundaries of the underlying SIMs.

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MS11

Weak-Form Parameter Inference of Epidemiological Systems

Compartmental modeling of epidemiological systems provides insights into biological and behavioral interactions that cannot be observed directly. Accurate and robust parameter estimation is critical to applying such models as decision-making tools for public health interventions. A common approach to parameter estimation is nonlinear least squares using a forward solver. However, as model size and noise in data increase these methods become computationally expensive to maintain accuracy in parameter estimates. The recently proposed Weak-form Estimation of Nonlinear Dynamics (WENDy) method is more accurate, robust to noise, and computationally efficient than forward solver-based approaches (even for higher dimensional systems). This method involves using carefully chosen test functions to convert the strong form representation of a model to its weak form, and estimating parameters by solving an equation error-based generalized least squares problem. In this talk, we will show that by using differential elimination algorithms we can convert ODE systems with unobserved compartments to weak form representations enabling WENDy to be applied when only a subset of the variables are measured (as occurs in epidemiological problems). Further, we will discuss the structural identifiability of these weak form systems and conditions where structural identifiability is preserved during the conversion from strong to the weak form representation.

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MS11

On the Relation Between Determining Modes and State Reconstruction

We will discuss the intimate interconnections between determining modes and the convergence of two particular filters, the synchronization filter and nudging filter, for continuous data assimilation in the context of the Navier-Stokes equation. The connection between determining modes and convergence of the algorithms is facilitated through a new concept we refer to as "intertwinement" of dynamical systems, whereas the connection between the synchronization filter and nudging filter is obtained by realizing the former as the object obtained in the infinite-nudging limit of the latter.

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MS11

State and Parameter Estimation from Partial State Observations of Stochastic Reaction Networks

Intra-cellular chemical reactions and are fundamental in the study of systems biology and are modeled by a class of continuous time Markov chains with a multidimensional non-negative integer lattice as state space. In addition to biochemical reactions, these models are also applicable in other forms population processes such as predator-prey systems and epidemiological models. We present recent results in the development of data assimilation methods for the estimation of states and parameters of a stochastic reaction network based on exact partial state observations. Two different cases are presented, one in which observations take place continuously in time while in the other, observations are made in snapshots of time. We provide derivations of our methods as well as numerical examples that illustrate the applicability of our approach.

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MS11

On the Identifiability of Avian Influenza Models

Avian influenza is an infectious disease that impacts both wild and domestic birds across the world. The transmission of avian influenza between humans is extremely rare, and it mostly affects people who are in close contact with infected family members. Although this scenario is uncommon, there have been multiple outbreaks that occur in small infection clusters with relatively low transmissibility and thus are too weak to cause an epidemic. Still, studying subcritical transmission events is vital for determining whether avian influenza is close to reaching the threshold of causing a widespread outbreak. In this presentation, we will discuss the structural and practical identifiability of an avian influenza model. Furthermore, we will explore how identifiability influences key epidemiological measures such as the basic reproduction number.

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MS12

Loxodromes in Open Multisection Lasers

We introduce a formalism to calculate lasing modes and optical power flow in multi-section lasers with open boundaries. The formalism uses a projection of the complex-valued electric field and its spatial derivative onto a suitably extended complex $\mathcal{Z}$-plane, to reduce the order of the problem and simplify analysis. In a single-section laser, we show that a laser mode is a *loxodrome* on the extended complex $\mathcal{Z}$-plane. In a multi-section laser, we obtain loxodromes for individual sections of the laser. Then, a multi-section mode is constructed by continuously concatenating individual loxodromes from each section using the open boundary conditions. A natural visualization of this construction is given by stereographic projection of the extended complex $\mathcal{Z}$-plane onto the Riemann sphere. Our formalism simplifies analysis of lasing modes in open multi-section lasers and provides new insight into the mode geometry and degeneracy.

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MS12

On the Integrability of Equations of the Nonlinear Schrdinger Type with Higher Orders of Dispersion

The propagation of high-intensity light pulses as they propagate through an optical fibre is principally affected by dispersion, the frequency-dependence of the refractive index, and the Kerr nonlinearity, the intensity-dependence of the refractive index. Under these conditions, light propagation is well described by the nonlinear Schrdinger equation. We consider here generalisations of the NLSE in which there are arbitrary higher orders of dispersion and which correspond to recent experiments in which soliton-like pulses were observed to be generated from noise. Focussing on soliton solutions which do not change their shape during propagation allows us to reduce the PDE to a corresponding ODE and the natural question is under what circumstances is that ODE integrable? We will prove that the resulting ODE fails the Painlev test in all cases except for the case of the original NLSE. We do this by considering the nature of singularities in the complex plane of solutions of the ODE and show that they have a number of movable branch points and relate this back to the properties of the soliton. We will focus on the example of pure quartic solitons since in this case the resulting ODE is a 4th order reversible nonlinear differential equation that has been extensively studied and so we can use our results to provide some insight into previous results.

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MS12

Regenerative Vectorial Breathers in a Delay-coupled Neuromorphic Microlaser with Integrated Saturable Absorber

We report on the polarization dynamics of regenerative light pulses in a micropillar laser with integrated saturable absorber coupled to an external feedback mirror. The delayed self-coupled microlaser is operated in the excitable regime, where it regenerates incident pulses with a suprathreshold intensity — resulting in a pulse train with interpulse period approximately given by the feedback delay time, in analogy with a self-coupled biological neuron. We report the experimental observation of vectorial breathers in polarization angle, manifesting themselves as a modulation of the linear polarized intensity components without significant modulation of the total intensity. Numerical analysis of a suitable model reveals that the observed polarization mode competition is a consequence of symmetry-breaking bifurcations induced by polarization anisotropy. Our model reproduces well the observed experimental results and predicts different regimes as a function of the polarization anisotropy parameters and the pump parameter. We believe that these findings are relevant for the fabrication of flexible sources of polarized pulses with controlled properties, as well as for neuroinspired on-chip computing applications, where the polarization may be used to encode or process information in novel ways.

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MS13

Discovering the Geometry of Blenders in a Three-Dimensional Hnon-Like Map

A dynamical system given by a diffeomorphism with a three-dimensional space may have a *blender*, which is a hyperbolic set Λ with, say, a one-dimensional stable invariant manifold that behaves like a surface. This means that the stable manifold of any fixed or periodic point in Λ weaves back and forth as a curve in phase space such that it is dense in some planar projection; we refer to this as the *carpet property*. Moreover, this property persists for small arbitrary perturbations. The presence of a blender can be used to prove the robust existence of a non-transverse heterodimensional cycle, which implies the so-called wild chaos. We present an algorithm for computing very long pieces of such a one-dimensional manifold that we implemented in Matlab to identify efficiently, accurately and reliably a very large number of intersection points with a specified section. With this method, we investigate the geometric properties of the emergence of blenders in a three-dimensional Hnon-like map $\mathcal{H}$ by computing the one-dimensional manifold of its fixed and periodic points. Specifically, we discover that the organisation of the projection of the intersection points follows a consistent pattern as a parameter is varied. Consequently, we can study in detail the specific parameter values and order of events that occur as the blender arises.

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MS13

Reconstruction of Dynamics by Reservoir Computing

Reservoir computing (RC) is a kind of machine learning method. In contrast to the deep learning which uses a (deep) feedforward network, RC uses a recurrent neural network (RNN), which itself may be thought of as a dynamical system (often of large degrees of freedom), hence RC is considered good for learning dynamics, such as time-series generated by a dynamical system. The purpose of this talk is to present a mathematical mechanism for learning dynamics by RC. We take, as a target of learning, an iterated map on a compact manifold having an attractor, and show that, when learning is successful, the reservoir dynamics holds an attractor that is semi-conjugate to the original one for learning. We can also show sufficient conditions for successful learning. Roughly speaking, for a good enough dynamical system such as C^1-diffeomorphism with a hyperbolic attractor (which is C^1-structurally stable), if the number of nodes of RNN of the reservoir system is sufficiently large, then generically the learning will be successful. We shall give several numerical experiments that suggest that a similar result may be expected for a larger class of dynamical systems, including non-invertible non-uniformly hyperbolic systems such as the logistic maps and the Hnon map, and higher dimensional systems. This talk is based on joint works with Masato Hara (Kyoto).

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MS13

Dynamics of Near-identity Maps and Interpolating Vector Fields

Interpolating vector fields (IVFs) provide a theoretical and a numerical tool to study dynamics of near-identity maps of any dimension [1]. We will show how to use IVFs in different contexts. As a first example, we will use IVFs to study the dynamics of a 4D quasi-integrable symplectic map in the chaotic regions near double resonances. Adapted visualization techniques allow to identify the relevant phase space objects in these regions. Moreover, numerical explorations of the long term dynamics will be supported with theoretical estimates based on IVFs [2]. As a second application, we will use IVFs to reveal some details of the bifurcation diagram of a dissipative Lorenz-like map and to give evidence of the existence of pseudo-hyperbolic discrete Lorenz attractors [3]. Further applications of IVFs to the study of conservative and dissipative systems will be also discussed. [1] V.Gelfreich and AV, Interpolating vector fields for near identity maps and averaging, Nonlinearity, 31(9):4263–4289, 2018 [2] V.Gelfreich and AV, Nekhoroshev theory and discrete averaging, arXiv preprint arXiv:2411.02190, 202 [3] A.Kazakov, A.Murillo, AV and K.Zaichikov, Numerical study of discrete Lorenz-like attractors, RCD 29(1), 77–98, 2024.

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MS14

The Non-Perturbative Adiabatic Invariant Is All You Need

Developing reduced models for highly-oscillatory dynamical systems traditionally proceeds by applying asymptotic averaging methods. However, the quality of asymptotic averaging degrades as timescale separation decreases. In studying a classical application of asymptotic averaging methods, charged particles moving in a strong inhomogeneous magnetic field, we identified a regime of marginal timescale separation where asymptotic averaging fails quantitatively in spite of strong indications that a good averaged model ought to exist. We developed a non-perturbative, data-driven averaging method for the marginal regime and found the resulting non-perturbative averaged model significantly outperforms asymptotic averaging, even when accounting for corrections from higher-order averaging. I will explain the method in general and in the charged particle context. Then I will report on results from the method's application to α-particle dynamics in a fusion reactor concept known as the stellarator.

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MS14

Chaotic Magnetic Fields in Hybrid Kinetic Plasma Equilibria

We construct a one-dimensional, quasineutral hybrid VlasovMaxwell equilibrium model with kinetic ions and massless fluid electrons to study travelling wave structures in collisionless plasmas, including cases with a background magnetic field. Our model determines the magnetic field by solving an inhomogeneous Beltrami equation, where the inhomogeneous term represents the ion current density and the homogeneous term represents the electron current density. We show that the 1-D system of equilibrium equations is a Hamiltonian system with position playing the role of time. For symmetric ion distributions, the wave structures exhibit periodic behavior, while asymmetric distributions yield nonintegrable, chaotic dynamics. Electron current density can alter the phase space of the Hamiltonian system, inducing orbit trapping and organizing orbits into stability islands. Hence, the electron current can be responsible for the emergence of localized electric field structures that induce ion trapping. We also present a method for constructing hybrid equilibria, allowing calculation of analytic magnetic fields and distribution functions based on the use of Hermite polynomials.

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MS14

Geometry of Beltrami Fields with Plasma Applications

We investigate the contact and symplectic geometry of non-vanishing Beltrami fields on the three torus. In particular, we use the zero level sets of the components of a Beltrami field to partition the three torus into subsets. These subsets are dependent on both the geometry and the homology type of the zero level sets and provide a way to analyze the flow as trajectories pass from subset to subset. We focus on the famous ABC flow and provide numerical simulations of ‘pseudo’-Poincaré maps determined by the zero level sets.

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MS14

Robustly Computing Higher-Dimensional Invariant Tori

Integrable trajectories in Hamiltonian dynamical systems are conjugate to simple translational motion on n-dimensional invariant tori. In practice, however, the shapes of invariant tori are rarely known analytically, nor does one typically know whether a trajectory is integrable a priori. Moreover, it is difficult to numerically parameterize these tori for non-perturbative systems, as most algorithms require good initial guesses for the rotation vector and/or the torus parameterization. In this talk, we will show how a sequence extrapolation method, dubbed Birkhoff reduced rank extrapolation (Birkhoff RRE), can classify invariant tori from a single trajectory without continuation or initial guesses. When the trajectory is integrable, Birkhoff RRE finds the rotation vector to high accuracy. Then, by projecting back on the trajectory, Fourier coefficients of the invariant torus are obtained. We demonstrate the algorithm with examples of charged particle motion from plasma physics.

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MS15

Swimming, Jumping and Crawling Robots Driven by Internal Oscillations

How should a force or torque be applied by an actuator to produce locomotion in a mobile robot? More abstractly, for a Lagrangian with a configuration manifold $Q = G \times S$, what changes in the shape variables produce fast motion on the group manifold G? The talk will describe examples of novel mobility due to periodic changes in internal degrees of freedom, that do not directly interact with the environment. A special case of such internal actuation is the spin of unbalanced rotors. Spinning unbalanced rotors transfer high-frequency reaction forces and moments that in turn can produce oscillations of flexible structures like tails in a fish-like robot and in legs or cilia in a soft robot. Further these spin-generated forces modulate the forces at surfaces producing discontinuous phenomena like slipping and jumping. The mobility described through these examples goes beyond the well-known geometric phase and occurs due to symmetry breaking by nonholonomic constraints or discontinuities in holonomic constraints. In this talk I will discuss several examples of unconventional mobility enabled by a spinning unbalanced rotor. These will include a spin-driven swimming robot which has a locomotion efficiency approaching that of several species of fish, a spin-driven pipe crawling robot and a spin-driven jumping robot. Spin is all one needs for versatile mobility.

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MS15

Dynamics of Single-Input Mobile Robots with Nonholonomic Constraints

This talk will analyze the mechanics of two planar mobile robots, each with a solitary internal degree of freedom, for which symmetry-breaking by nonholonomic constraints leads to nontrivial reduced-order dynamics. The discussion of each system — a Chaplygin sleigh surmounted by an imbalanced rotor and a two-link snakelike robot with passive wheels — will serve to preface a subsequent talk in the session. System features to be explored include Lagrangian and Hamiltonian structure, bifurcations of relative equilibria, chaotic trajectories, and amenability to underactuated control.

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MS15

Simple Snakelike Robots in Shared Environments: Coupling and Control

When birds fly or fish swim in a dense formation, individuals are coupled mechanically to their neighbors through the dynamics of the surrounding fluid. This coupling may be viewed in a variety of ways, from a means to exchange information through mutual sensing to a means whereby one individual can exert control forces on another. A simplified environment in which to study similar mechanical communication within multi-agent systems is realized when mobile robots are placed atop a common solid platform with finite mass, subject to the conservation of momentum in the system overall. This talk concerns the dynamics and control of systems of wheeled snakelike robots atop shared platforms. Problems of synchronization and control will be analyzed for two- and three-link robots with combinations of directly controlled, entirely passive, and elastically compliant internal joints.

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MS15

Controlling Shape and Position with Salp-Inspired Distributed Thrust

Salps are marine animals consisting of chains of jellyfish-like entities. Their capacity for effective underwater undulatory locomotion through coordinating multi-jet propulsion has aroused significant interest in the field of robotics and inspired extensive research including mechanism design, hydrodynamic modeling, motion planning, and control. In this work, we conduct a comprehensive analysis of the locomotion of salps using the robotic platform ”LandSalp” based on geometric mechanics, including mechanism design, dynamic modeling, system identification, and motion planning and control. Our work takes a step toward a better understanding of salps' underwater locomotion and provides a clear path for extending these insights to more complex and capable underwater robotic systems. More importantly, this study illustrates the effectiveness of geometric mechanics in bio-inspired robots for efficient data-driven locomotion modeling, demonstrated by learning the dynamic model of LandSalp from only 3 minutes of experimental data. Lastly, we extend the geometric mechanics principles to multi-jet propulsion systems with stability considerations and validate the theory through experiments on the LandSalp hardware.

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MS16

Estimation of Metabolic Parameters Using a Machine Learning

Estimating metabolic parameters related to glucose homeostasis, such as insulin sensitivity and beta-cell function, is crucial for preventing diabetes progression and managing diabetes in patients. The oral glucose tolerance test (OGTT) is a standard clinical assessment that evaluates the performance of organs and tissues in glucose metabolism. A mathematical model of glucose homeostasis (Ha et al., AJP Endocrinology and Metabolism, 2024) has been developed to estimate insulin sensitivity and beta-cell function during OGTTs. However, OGTTs are time-consuming and costly, making them less practical for routine clinical use. To address this, surrogate markers estimated from fasting measurements, such as HOMA-IR and HOMA-B, are commonly used in practice. In this study, we aimed to improve predictions of insulin sensitivity and beta-cell function during OGTTs using a machine learning approach with fasting measurements as inputs. Using the Africans in America dataset, which includes OGTT results for African immigrants in the US ($N = 612$), we applied a support vector machine (SVM) with 8-fold cross-validation. Fasting glucose, insulin, and HbA1c were used as inputs, yielding strong predictive performance for insulin sensitivity and beta-cell function ($R = 0.73$, 0.61, P ¡ 0.001), and outperforming HOMA-IR and HOMA-B.

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MS16

Differential Equation Driven Machine Learning Methods for Modeling of Dynamical System

Parameter estimation for nonlinear dynamical systems is a crucial task in various areas, including biomedical applications. These parameters are key elements that determine the causal structure of the solutions to the underlying differential equations governing the system. Machine learning methods for parameter estimation are usually designed without prior knowledge of the system dynamics, relying on data-driven approaches to find empirical relations. In this talk, we will consider various machine learning methods that combine differential equations with neural networks, such as recurrent neural networks and time-delay neural networks. We will discuss how to integrate prior knowledge into these models and demonstrate their application in parameter estimation for diabetes models.

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MS16

Integrating Data-Driven and Dynamics-Driven Approaches for Predicting Glucose and Insulin Response: An Physics-Informed Rnn-Based Solution for Ogtt with Initial Measurements Only

The oral glucose tolerance test (OGTT) is commonly used for diabetes diagnosis, requiring glucose and insulin measurements over a 120-minute period. This process, however, is time-consuming and costly, imposing challenges for patients and healthcare providers. To address these limitations, we propose a machine learning model that predicts glucose and insulin levels over a 2-hour period using only initial glucose and insulin values as inputs. Our approach leverages a recurrent neural network (RNN) for time-series forecasting, specifically exploring the connection between RNN algorithms and ordinary differential equation (ODE) modeling. By implementing a physics-informed loss function, we enable the RNN to learn glucose and insulin dynamics that align with traditional ODE-based models. This integration optimizes the RNN to provide a robust, dynamically suitable solution that combines the strengths of data-driven predictions with mathematical modeling for improved accuracy and resilience against anomalies.

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MS16

Fitting a Multi-Timescale Mathematical Model to Longitudinal Data

Type 2 diabetes (T2D) is a chronic disorder of glucose homeostasis caused by dysfunction across multiple organs and tissues. A common pathophysiological feature of T2D is the inability of insulin-secreting pancreatic beta-cells to meet the bodys insulin demand, which is necessary to maintain normal blood glucose levels. For each patients diabetes intervention and therapy, accurately estimating an individuals beta-cell secretory capacity is crucial for predicting T2D progression. Recently, a mathematical model of T2D has been developed to enhance our understanding of the disease's pathophysiology (Ha and Sherman, AJP, 2020). In this presentation, we aim to fit the model to longitudinal data to estimate a key metabolic parameter associated with beta-cell secretory capacity. Given that model operates on multiple timescales, incorporating both fast and slow dynamics, we divided the fitting process into two steps. In step 1, we treat the slow variables of the model as parameters and fit the resulting fast subsystem of the model to data collected at each time point to estimate the slow variables. Using these estimates, we then fit the full model to the entire longitudinal dataset to estimate the key metabolic parameter related to beta-cell secretory capacity.

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MS17

Geostrophic Turbulence and the Formation of Large Scale Structure

Rotating convection is a prototypical system at the core of geophysical fluid dynamics. However, the parameter values for geophysical flows take values that are far outside those that can be studied in the laboratory or via state of the art numerical simulations. In this talk I will describe a formal asymptotic procedure that leads to a reduced system of equations valid in the limit of very strong rotation. These equations describe four regimes as the Rayleigh number Ra increases: a disordered cellular regime near threshold, a regime of weakly interacting convective Taylor columns at larger Ra, followed for yet larger Ra by a breakdown of the convective Taylor columns into a disordered plume regime characterized by reduced heat transport efficiency, and finally by a type of turbulence called geostrophic turbulence. Properties of these states will be described and illustrated using direct numerical simulations of the reduced equations. These simulations reveal that geostrophic turbulence is unstable to the formation of large scale barotropic vortices or jets, via a process known as spectral condensation. The details of this process will be quantified and its implications explored. The predictions from the reduced equation shave been corroborated via direct numerical simulations of the Navier-Stokes equations, albeit at much more modest rotation rates, confirming that the reduction procedure captures the essence of the problem.

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MS17

Marangoni Convection in Non-Isothermal Surfactant Solutions

The Marangoni convection, which is induced by interfacial tension gradient associated with either solutal or thermal gradients or their combination, has an important influence on interfacial heat and mass transfer processes. It is a typical non-equilibrium physical phenomenon, characterized by a variety of spatiotemporal periodic patterns. The pattern forming process is especially crucial in thin liquid layers, where the interfacial effects prevail over the bulk processes. The origin of the large-scale stationary or wave patterns is a result of long-wavelength instabilities. Near the instability threshold, reducing the description of the dynamics of the system to three coupled nonlinear equations for temperature fluctuations, deviation of the fluid thickness, and surfactant concentration we can obtain the conditions of the formation of structures. In this lecture we review the latest results in large-scale Marangoni convection in non-isothermal surfactant solutions. The weakly nonlinear approach proposed by Newell and Whitehead, describing the interaction of the disturbances with various wavenumbers close to the critical one, is applied to analyze the formation and modulation of patterns on different lattices in the

Fourier space near the instability threshold.

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MS17

Stochastic Model for the Laminar-turbulent Transition in Pipe Flow

In transitional pipe turbulence, a sequence of phases is observed experimentally in the range of Reynolds numbers between 1900 and 5000, passing through the laminar-turbulent transition at Re 2040. These phases are characterized by transient decay of puffs (Re ¡ 2040), puff-splitting and propagation (2040 ¡ Re ¡ 2250), expansion of turbulent regions via weak slugs (asymmetric upstream and downstream fronts, 2250 ¡ Re ¡ 4500), and via strong slugs (symmetric upstream and downstream fronts, Re ¿ 4500). Here, we present a stochastic model for the decay, splitting, and propagation of turbulent patches in a background laminar flow. The model represents the energy budget of the flow in terms of stochastic predator-prey (or activator-inhibitor) dynamics, where mean azimuthal flows, activated by incipient small-scale turbulence, inhibit the turbulence, leading to a complex puff and slug dynamics. The resulting model recapitulates the full phase diagram of the transition, successfully capturing the mechanism of puff splitting and pushing and the puff-slug transition. The model is not restricted to pipe flow geometry and is extendable to other transitional shear flows like quasi-one-dimensional Taylor-Couette flow.

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MS17

Excitable Solitons in Mass-conserving Reaction-diffusion Media: Annihilation, Crossover, and Nucleation After Collisions

Excitable pulses are among the most widespread dynamical patterns in many dissipative systems, ranging from biological cells to chemical reactions and ecological populations. Traditionally, the mutual annihilation of two colliding pulses is regarded as their prototypical signature. However, in a model of intracellular actin waves described by a mass-conserved reaction-diffusion model, we show, using a bifurcation theory about a T-point of heteroclinic and homoclinic orbits (in space), why colliding excitable pulses may exhibit soliton-like crossover and pulse nucleation features. In contrast to dissipative models, these alternative collision scenarios are robust and observed over a wide range of parameters owing to the presence of a generic subcritical long-wavenumber bifurcation.

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MS18

Koopman Operator Approach to Definition of Rotation Numbers in Dynamical Systems

In this work, we leverage the spectral analysis of pullback operators associated with a dynamical system, viewed as generalized Koopman operators, to introduce a generalized form of the Ruelle rotation number. This spectral approach is well-defined for systems of arbitrary dimension, thereby extending the applicability of the Ruelle rotation number beyond its traditional scope, which was originally limited to symplectic or low-dimensional systems.

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MS18

When do Koopman Embeddings Exist?

Given scalar observations of an unknown nonlinear dynamical system, extended Dynamic Mode Decomposition (eDMD) seeks to model the time-evolution of these observables by a linear dynamical system. To avoid information loss and numerical challenges, one often wants the collection of observables to separate points and be continuous (or smoother). Stacking such observables into a vector-valued function yields a globally linearizing "Koopman embedding" of the nonlinear system, which, conceptually, embeds the nonlinear system as an invariant subset of a linear system of greater or equal dimension. However, Koopman embeddings do not generally exist, posing a fundamental challenge for eDMD and related algorithms. In this talk, I will present necessary and sufficient conditions for the existence of Koopman embeddings for a broad class of nonlinear systems. Time permitting, I will also present a counterexample to the oft-repeated claim that nonlinear systems with multiple isolated equilibria do not admit a smooth (or even continuous) Koopman embedding. Aspects of this talk are based on joint work with Philip Arathoon and with Eduardo D. Sontag.

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MS18

Representations of the Koopman Operator and System Identification

The Koopman (composition) operator theory provides a framework for connecting machine learning, dynamical systems and control theory. In this paper we combine ideas from these fields. The concept of dynamical system representation is used to inform data-driven system identification methods. The notion of linear representations is clarified and shown to lead - in general - to linear evolution on nonlinear sets, enabling linear representations for systems with nontrivial attractors such as limit cycles. The concept of Koopman control family is connected to the notion of nonlinear representations and the associated spectral problems are studied.

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MS18

Participation Factors for Nonlinear Dynamical Systems in the Koopman Operator Framework

We devise a novel formulation and propose the concept of modal participation factors to nonlinear dynamical systems. The original definition of modal participation factors (or simply participation factors) provides a simple yet effective metric. It finds use in theory and practice, quantifying the interplay between states and modes of oscillation in a linear time-invariant (LTI) system. In this talk, with the Koopman operator framework, we present the results of participation factors for nonlinear dynamical systems with an asymptotically stable equilibrium point or limit cycle. We show that participation factors are defined for the entire domain of attraction, beyond the vicinity of an attractor, where the original definition of participation factors for LTI systems is a special case. Finally, we develop a numerical method to estimate participation factors using time series data from the underlying nonlinear dynamical system. The numerical method can be implemented by leveraging a well-established numerical scheme in the Koopman operator framework called dynamic mode decomposition.

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MS19

On Sharp Estimates and Computer Assisted Proofs in Kam Theory

In recent years, a posteriori KAM theorems, based on the parameterization method, have been used to compute and validate numerical approximations of quasi-periodic orbits, as well as to prove the existence of invariant tori. The conditions for validation depend on the smallness of Diophantine constants and the width of the analyticity strips of the parameterizations of the tori. Reducing the impact of this smallness could significantly enhance the efficiency of computer-assisted proofs. In this talk, we present various contexts where sharp estimates can be obtained for KAM theorems based on the parameterization method.

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MS19

A Spectral Approach to Computer-assisted Proofs in Dynamics: Part II

Using the spectral framework for computer assisted proofs introduced by J.B. van den Berg in part I, I'll discuss several applications involving invariant manifolds and periodic orbits in problem areas like celestial mechanics and carbon cycle modeling.

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MS19

A Spectral Approach to Computer-assisted Proofs in Dynamics: Part I

Finding solutions to problems in nonlinear dynamics often involves simulations. Turning such numerical computations into mathematical theorems requires computer-assisted proofs. Although such proofs focus on specific solutions (or invariant objects more generally) to specific equations, in this talk we take a more universal viewpoint and describe a relatively simple framework in which many of these problems can be cast. In particular, since these systems and their solutions are usually locally analytic, one can recast the problem into one concerning sequence spaces of rapidly decaying coefficients, say of a Taylor, Fourier or Chebyshev series. The core of the analysis is then to manipulate such sequences, e.g. evaluating derivatives and nonlinearities, by computer, while keeping track of truncation and rounding errors. In this talk we discuss how one can use basic complex and Fourier analysis to accomplish this task for a wide variety of problems in nonlinear dynamics. Such a unified approach can simplify both the analysis and the code.

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MS19

Three-Dimensional Periodic Solutions in the Forced Navier-Stokes Equations

In this work, we extend results from existing literature on periodic solutions in the forced Navier-Stokes equations from two to three dimensions. Our approach relies on computer-assisted proof methods, based on a Newton-Kantorovich type argument, ensuring rigorous control over computational errors. Challenges posed by the higher-dimensional nature of the problem are alleviated by employing symmetry arguments. In this study, we focus on traveling wave solutions and on validating solutions at, and near, the Hopf bifurcations.

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MS20

Spectral Persistence Applied to Bacterial Aggrega-

tion Dynamics

We present a novel method for identifying structural features in high-dimensional datasets, with applications in colony dynamics and material science. Traditional Topological Data Analysis (TDA) techniques, such as persistent homology, often face computational challenges in high dimensions due to the resource-intensive process of constructing and processing simplicial complexes. Our method offers an alternative by defining a distance function on the dataset and applying a Fast Fourier Transform (FFT) combined with a Butterworth filter to smooth this distance function.

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MS20

Modeling Foraging Ant Dynamics in Multiple Food Source Environments

Foraging for resources is an essential process for the daily life of an ant colony. What makes this process so fascinating is the self-organization of ants into trails using chemical pheromone in the absence of direct communication. Here we discuss a stochastic lattice model that captures essential features of foraging ant dynamics inspired by recent agent-based models while forgoing more detailed interactions that may not be essential to trail formation. Nevertheless, our models results coincide with those presented in more sophisticated theoretical models and experiments. Furthermore, it captures the phenomenon of multiple trail formation in environments with multiple food sources. This latter phenomenon is not described well by other more detailed models. We also discuss a complementary macroscopic PDE which captures the basic structure of lattice model. The PDE provides a continuum framework for the first-principle interactions described in the stochastic lattice model and is amenable to analysis. Linear stability analysis of this PDE facilitates a computational study of the impact various parameters impart on trail formation. We also highlight universal features of the modeling framework that may allow this simple formation to be used to study complex systems beyond ants.

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MS20

Dynamics of active rod colonies under confinement

Active rods, which serve as a model for many biological and biomimetic micro-swimmers, exhibit intriguing phenomena under imposed flow conditions with confinement, such as boundary accumulation and upstream swimming. Additionally, colonies of active rods respond nontrivially to wall geometry, tending to accumulate at locations of highest curvature and in corners. These phenomena significantly influence how active rods are transported through microchannels. First, we use computational methods to study a dilute suspension of active rods and how their extrusion through microchannels can be controlled by cross-sectional geometry. We also investigate the role of wall torque exerted on accumulated active rods. For flat walls, this torque reorients the active rods to be tangent to the wall, allowing them to escape. We demonstrate, both theoretically and numerically, that in the case of a curved wall, entrapment at locations of highest curvature can be stable, even when considering wall torque. Finally, I will discuss a kinetic approach that allows for the direct computation of the probability distribution function of the active rods location and orientation. A distinguishing feature of this approach is that it takes into account the wall accumulation of rods and includes two probability distribution functions: one for rods in the bulk and another for accumulated rods. This is a joint work with Chase Brown (UC Riverside) and Shawn Ryan (Cleveland State University).

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MS20

Topological Data Analysis of Biological Aggregations

A time-varying collection of metric spaces as formed, for example, by a moving school of fish or flock of birds, can contain a vast amount of information. There is often a need to simplify or summarize the dynamic behavior. Algebraic topology can provide a lens to understand complex data by studying its shape. One such method is a crocker plot, a 2-dimensional image that displays the topological information at all times simultaneously. We discuss how this method has shown promise in a variety of contexts: to perform exploratory data analysis, to choose between two models of collective motion, and to investigate parameter recovery via machine learning.

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MS21

A Non-Intrusive Framework for Learning Corrections to Long Time Climate Simulations from Short Time Training Data

Quantifying the risks of extreme weather is becoming increasingly difficult due to our rapidly changing climate and yet remains critical in the implementation of strategies to mitigate its impact. The vast range of scales in the Earths turbulent atmosphere renders direct numerical simulation intractable over the multi-century time horizons needed for converged rare event statistics. On the other hand, coarse simulations that parametrize or insufficiently resolve the dynamics at the smallest scales generally suffer from an inability to generalize beyond the parameter regimes for which they were designed. This is because these sub-grid scales nontrivially affect the dynamics and statistics of large-scale phenomena in ways that are not universally understood. Here we present machine learning framework to correct the output of long-time coarse-resolution climate simulations. The framework – which acts as a post-processing operation – relies on training data pairs that have minimal chaotic divergence namely a reference trajectory and a coarse simulation nudged towards that reference. Training on these specific trajectories allows us to generalize to unseen chaotic climate realizations of arbitrary length. Furthermore, the post-processing nature ensures that our method is stable. We illustrate our approach on the E3SM climate model with 100km resolution, where with only 8 years of training data we can significantly reduce the error in global and regional 40-year statistics.

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MS21

Dynamical System Identification Via Invariant Measures in Time-Delay Coordinates

Invariant measures are widely used to compare chaotic dynamical systems, as they offer robustness to noisy data, uncertain initial conditions, and irregular sampling. However, large classes of systems with distinct transient dynamics can still exhibit the same asymptotic statistical behavior, which poses challenges when invariant measures alone are used to perform system identification. Motivated by Takens' seminal embedding theory, we propose studying invariant measures in time-delay coordinates, which exhibit enhanced sensitivity to the underlying dynamics. We present theoretical results which show that, up to a topological conjugacy, the delay-coordinate invariant measure can distinguish between dynamical systems, and we provide numerical examples which demonstrate the utility of our proposed method.

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MS21

Data-Driven Closure Modeling Using Derivative-Free Kalman Methods

Closure problems are critical in predicting complex dynamical systems, e.g., turbulence or cloud dynamics, for which numerically resolving all degrees of freedom remains infeasible in the foreseeable future. Although researchers have been advancing traditional closure models of those systems for decades, the performance of existing models is still unsatisfactory in many applications, mainly due to the limited representation power of existing models and the associated empirical calibration process. Recently, the rapid advance of machine learning techniques has shown great potential for improving closure models of dynamical systems. In this talk, I will share some progress in data-driven closure modeling for complex dynamical systems. More specifically, I will demonstrate the use of derivative-free Kalman methods to learn stochastic closure models from indirect and limited amount of data. Hybrid use of gradient-based and derivative-free methods to leverage both short-term trajectories and long-term statistics data will also be demonstrated in the context of operator learning.

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MS22

Phenotype-Driven Mathematical Approaches for T-Cell Activation

T-cells scan lymphoid tissues for antigens on APCs, triggering immune responses via TCR recognition on pMHC molecules. McKeithans KPR model (McKeithan, Kinetic proofreading in T-cell receptor signal transduction, 1995) introduced the concept of biochemical modifications in the TCR-pMHC complex. Later models, like KPR with limited signal duration and sustained signaling, aimed to explain T-cell traits such as prolonged pMHC half-lives, non-transmission of downregulation signals, and the intermediate dwell time needed for signaling. However, no model fully captures all traits. A notable model is the TCR negative signaling model by Franois et al. (P. Franois, Phenotypic model for early T-cell activation displaying sensitivity, specificity, and antagonism, 2013), further examined by Rendall et al. (A. D. Rendall, Multiple steady states and the form of response functions to antigen in a model for the initiation of T-cell activation, 2017), which reveals steady-state multiplicity and non-monotonic response. My talk will compare these models using experimental parameters to determine which best explains T-cell activation, replicating Rendall et al.'s mathematical findings with experimentally derived parameters, offering insights into T-cell activation models' phenotypic and mathematical traits.

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MS22

A Characterization of the Detailed Balance Property in Chemical Networks

The aim of this talk is to study under which conditions it is possible to understand if a chemical network satisfies the detailed balance property (i.e. if it operates at equilibrium or out of equilibrium) without knowing the details of the chemical reactions taking place in the network. To access the properties of the chemical network, we assume that few measurements are possible. In this context a measurement is a function $R_{ij}(t)$ which is given by the concentration of the substance j at time t, after the injection of a substance i at time $t = 0$. We obtain a condition involving $R_{ij}(t)$ and $R_{ji}(t)$ that is necessary, but not sufficient for the detailed balance property to hold in the network. Moreover, we prove that this necessary condition is also sufficient if a topological condition is satisfied, as well as a stability property that guarantees that the chemical rates are not fine-tuned.

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MS22

Population Dynamics of Competing Species in Driven And/or Spatially Inhomogeneous Systems

We study stochastic population dynamics subject to time- and/or space-dependent rate parameters, specifically: 1) To represent seasonal oscillations in resource availability, we implement a periodically varying carrying capacity in a lattice Lotka-Volterra predator-prey model. Two-species coexistence is enhanced by this periodic drive. The fast and slow switching regimes are described through different effective static environments. Resonant features emerge when the external switching rate matches the internal population oscillation frequency, inducing persistent spatial correlations. 2) Stochastic population dynamics in finite systems often ultimately terminates in an absorbing state. Yet, in sufficiently large spatially extended models, the time to reach species fixation / extinction becomes exceedingly long, effectively permitting coexistence. Yet tuning certain control parameters, e.g., increasing the predation rate in predator-prey systems or enhancing asymmetries in cyclic dominance models, may render coexistence states in finite systems highly vulnerable against intrinsic fluctuations. We show how such systems may be stabilized through continuous influx from their boundaries, which is generated via diffusive coupling of the volatile region to an adjacent stable patch. Semi-quantitative criteria delineate the conditions for this boundary flow stabilization of finite-size absorbing-state instabilities in systems with either cyclic or hierarchical competition.

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MS23

Mathematical Modeling of Melatonin and Its Action on the Circadian Clock

The pineal secretion of the hormone melatonin demonstrates a circadian (24 h) rhythm with the onset of melatonin production at night and offset each morning under tight control of the circadian pacemaker in the suprachiasmatic nucleus (SCN). Melatonin exerts both acute sleep-promoting effects and chronobiotic effects on the circadian clock, and exogenous melatonin supplements are increasingly being used as a treatment for a variety of sleep and circadian diseases and disorders. Phase shifting of the circadian clock in the SCN can also be accomplished through ocular exposure to light. However, the interacting effects of light and melatonin on the circadian clock are not well understood. To analyze the dynamic behavior of both endogenous and exogenous melatonins influence on the circadian clock, we extend a macroscopic mathematical model of collective activity of SCN neurons to account for melatonin forcing and integrate it with a model of melatonin dynamics that describes both endogenous melatonin produced by the pineal gland and exogenous melatonin entering the system through ingested oral supplements. This modeling framework allows for the study of melatonins dynamic properties and provides insight into optimal light exposure and exogenous melatonin administration schedules to induce desired phase shifting of the circadian clock.

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MS23

From the Method of Averaging to a Numerical Method to Simulate Neuronal Populations

Noisy oscillators arise in the modeling of many scientific problems, particularly in physics, neuroscience, ecology and climate studies. Phase reduction is a traditional approach that simplifies the dynamics. However, the assumption of weak noise in phase reduction limits its application. Particle methods, on the other hand, provide more accurate results, but are often computationally expensive. It is important to note that these two approaches are not necessarily exclusive to each other, and an appropriate integration can give rise to more efficient simulation of the noisy oscillator models. In this work, we present how phase reduction techniques can be incorporated into particle methods to study population level behaviors of noisy coupled oscillators. We use elliptical Gaussian basis functions to solve the Fokker-Planck equation that describes the evolution of the probability density function. We propose an original particle shrinking method based on phase reduction. Our method reduces the number of particles and accelerates the particle updating process, thereby achieving higher computational efficiency. At the same time, we preserve the structure of the possibly high-dimensional state space, which avoids oversimplification. In particular, we show that this method is well adapted to systems with relaxation oscillation. As illustration, we apply our method to 4-dimensional and 5- dimensional Hodgkin-Huxley type neuronal models.

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MS23

Coupled Oscillatory Circuits and Beta Rhythm Generation

Several different neuronal feedback loops in the basal ganglia have been considered as possible generators of the beta-band oscillations that become exaggerated in Parkinson's disease. Different studies have produced conflicting results about how these loops interact. It has been posited that interacting excitatory-inhibitory (E-I) and purely-inhibitory loops are essential for beta generation, yet also that the E-I loop attenuates beta arising from the all-I loop. Our work seeks to resolve this contradiction by proposing a unified framework that captures the loops' combined influence on beta oscillatory activity. Specifically, using phase plane and bifurcation analysis and other methods, we show how phase-locking and cooperation or interference between the loops depend on factors such as the form of the model equations used for the analysis and the relationshipbetween the features of the loops' intrinsic dynamics. Our findings suggest that the interaction between these two loops can play a dynamic, context-dependent role in the emergence of beta oscillations, with implications forbasal ganglia function in both health anddisease.

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MS23

Functional Variability in Sequence Intervals that Build Neural Rhythms

Neural rhythms are typically characterized by oscillations and quantified by frequencies, ranging from small circuits to human EEG. Many of these rhythms involve robust sequential activations of constituent neurons, networks, or neural systems. However, characterizing and quantifying neural sequences is more challenging than assessing and quantifying macroscopically observed oscillations. Consequently, sequential activations have received less attention from the neuroscience community, particularly in theoretical views of brain function. In this work, I will present several examples of robust sequential activations at multiple description levels of the nervous system. I will illustrate the concept of sequential dynamical invariants between intrinsically variable time intervals that nonetheless form robust sequences. Furthermore, I will discuss how this concept can be used to propose a theoretical framework and associated models for the description of multiscale neural information processing. This framework has potential applications in designing novel neurotechnologies for clinical use and in the field of biohybrid robotics.

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MS24

Traveling Waves, Reflections, and 1D Spiral Waves in Models of Cardiac Tissue

Each beat of the heart is triggered by a propagated wave of electrochemical excitation, called an action potential, that propagates in a coordinated manner through our heart tissue. Usually, when a propagated cardiac action potential interacts with a local tissue heterogeneity such as a region of depressed excitability or an abrupt change in geometry, either the action potential is blocked and annihilated, or it successfully propagates across the heterogeneity. However, in some cases, action potentials can successfully cross the heterogeneity and then give rise to a reflected action potential, i.e., an action potential that propagates in the retrograde direction. These reflected pulses can lead to the onset of life-threatening arrhythmias. The mechanisms that generate reflected pulses are not well understood, but their existence has been linked to the existence of an unstable spatiotemporal periodic orbit that has been referred to as a 1D spiral wave. 1D spiral waves are 'source defects' that consist of a non-excited core that sheds anti-phase counter-propagating pulses. The link between reflection, 1D spiral waves, and the induction of cardiac arrhythmias make it crucial to clarify the underlying mechanisms that give rise to 1D spiral waves and to identify conditions for which they exist. In this talk, we will discuss the link between reflected waves and 1D spirals in excitable media and describe the bifurcation scenario leading to the existence of 1D spirals.

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MS24

Optogenetic Feedback Control of Cardiac Arrhythmias

Malignant cardiac tachyarrhythmias are associated with complex spatiotemporal excitation of the heart. The termination of these lifethreatening arrhythmias requires high-energy electrical shocks that have significant side effects, including tissue damage, excruciating pain, and worsening prognosis. This significant medical need has motivated the search for alternative approaches that mitigate the side effects, based on a comprehensive understanding of the nonlinear dynamics of the heart. Cardiac optogenetics enables the manipulation of cellular function using light, enhancing our understanding of nonlinear cardiac function and control. Here, we investigate the efficacy of optically resonant feedback pacing (ORFP) to terminate ventricular tachyarrhythmias using numerical simulations and experiments in transgenic Langendorff perfused mouse hearts. We show that ORFP outperforms the termination efficacy of the optical single-pulse (OSP) approach. When using ORFP, the total energy required for arrhythmia termination, i.e., the energy summed over all pulses in the sequence, is 1 mJ. With a success rate of 50%, the energy per pulse is 40 times lower than with OSP with a pulse duration of 10 ms. We demonstrate that even at light intensities below the excitation threshold, ORFP enables the termination of arrhythmias by spatiotemporal modulation of excitability inducing spiral wave drift.

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MS24

Alternate Pacing and Chaos

We investigate, both experimentally and theoretically, the period-doubling bifurcation to alternans in heart tissue. We examine the impact of strategically perturbing an underlying dominant frequency, which we define as alternate pacing, to better understand how small deviations impact electrical response. We will share our experimental results in hearts excised from an adult bullfrog (Rana catesbeiana) and discuss the impact of temperature on the bifurcation to alternans. Furthermore, we will show how this experiment lead to an in-depth investigation of alternate pacing in the logistic map. We will also discuss how calculations involving alternate pacing and system noise can led to a methodical technique to explore chaos. More specifically, by computing the power spectrum from differences in the chaotic data trajectory, we will share underlying features of the trajectory.

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MS24

A Domain Decomposition Framework for Multiphysics Modeling of Cardiac Radiofrequency Ablation

Cardiac radiofrequency ablation (RFA) is a key therapeutic technique used to terminate arrhythmias by selectively heating and destroying targeted tissue areas. Accurate RFA modeling is essential for optimizing treatment outcomes and minimizing complications. RFA presents a complex, inherently multiphysics and multidomain problem, but current models often rely on simplified assumptions and one-way coupling or monolithic approaches across heterogeneous domains. This study introduces a comprehensive physics- and domain-decomposition (DD) approach for cardiac RFA modeling, extensible to various tissue types (e.g., kidney, uterine, hepatic) and energy sources (RF, microwave, ultrasound, laser). The model encompasses three primary domainselectrode, fluid, and tissueand integrates heat transfer, electrostatics, fluid dynamics, and a three-state cell-death model for lesion assessment. Some processes are confined to single compartments (e.g., fluid dynamics in fluid, cell-death in tissue), while others (e.g., electrostatics, heat transfer) are solved across domains. Various DD strategies, including Neumann-Dirichlet and Robin-Robin, are investigated and supported by a rigorous convergence. The scalable, high-order implementation in the MFEM library leverage GPU acceleration and efficient partially assembled operators for high computational performance. Results demonstrate the models potential for high-fidelity, efficient simulations in cardiac RFA and beyond.

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MS25

Lagrangian Chaos for the 2D Navier-Stokes Equations with Degenerate Stochastic Forcing

Keefer Rowan and I recently proved exponential scalar mixing for the 2D Navier–Stokes equations with a degenerate stochastic forcing considered in the work of Hairer and Mattingly '06. I will discuss a key intermediate step in our proof: positivity of the Lyapunov exponent for the Lagrangian one-point process. We follow the general strategy of Bedrossian, Blumenthal, and Punshon-Smith '21, '22, '22, where mixing (and more) for the same model with non-degenerate forcing was proven. This will be a sequel to Keefer Rowan's talk.

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MS25

A Harris Theorem for Enhanced Dissipation

In many situations, the combined effect of advection and diffusion enhances dissipation. One situation of interest is when the underlying flows are exponentially mixing. In this case a heuristic argument indicates that enhanced dissipation should be observable on time scales of order $O(|\log \kappa|)$, where κ is the molecular diffusivity. We will prove a Harris theorem and construct a class of random flows which are exponentially mixing, and exhibit enhanced dissipation on time scales of order $O(|\log \kappa|)$. In particular, our result implies that the randomly shifted alternating shears of Pierrehumbert exhibit enhanced dissipation on $O(|\log \kappa|)$ time scales. This is joint work with SJ Son and W. Cooperman.

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MS25

Mixing and Ideal Dynamo with Randomized Abc Flows

In this work we consider the Lagrangian properties of a random version of the Arnold-Beltrami-Childress (ABC) vector fields in a three-dimensional periodic box. We prove that the associated flow map possesses a positive top Lyapunov exponent, and its associated one-point, two-point and projective Markov chains are geometrically ergodic. For a passive scalar, it follows that such a velocity is a space-time smooth exponentially mixing field, uniformly in the diffusivity coefficient. For a passive vector, it provides an example of a universal ideal (i.e. non-diffusive) kinematic dynamo.

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MS25

Exponential Scalar Mixing for the 2D Navier-Stokes Equations with Degenerate Stochastic Forcing: Set-up and Model

I discuss recent work with William Cooperman in which we prove the presence of various passive tracer phenomena in the physical model of a fluid with large-scale stirring given by the 2D Navier–Stokes equations with a degenerate stochastic forcing considered in the work of Hairer and Mattingly '06. The passive tracer phenomena were proved for the case of non-degenerate forcing by Bedrossian, Blumenthal, and Punshon-Smith '21, '22, '22. Our work can be viewed as a union of these frameworks. This talk will focus on the set-up for the problem and the model of the degenerately forced fluid equation. William Cooperman's talk will focus on the proof of Lagrangian chaos.

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MS26

Opinion Dynamics on Graphons

In this work we make use of graphon theory to study opinion dynamics on large undirected networks. The opinion dynamics models that we take into consideration allow for negative interactions between the individuals, i.e. competing entities whose opinions can grow apart. We consider both the repelling model and the opposing model that are studied in the literature. We define the repelling and the opposing dynamics on graphons and we show that their initial value problems solutions exist and are unique. We then show that the graphon dynamics well approximate the dynamics on large graphs that converge to a graphon. This result applies to large random graphs that are sampled according to a graphon.

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MS26

Collective Variables in Dynamical Systems on Networks

This introductory talk approaches the topic of emergent collective dynamics on networks using the notion of collective variables (CVs). A collective variable maps the high-dimensional system state to a low-dimensional aggregated state by retaining exactly the state information that determines medium and large time-scale system behavior while filtering out unnecessary degrees of freedom that only have a short time-scale impact. For example, in mean-field theory the macroscopic system behavior is described by considering an average node, i.e., the underlying CV averages over the states of the nodes. In this talk, I will outline how the existence of such CVs implies that a reduced model describing the emergent collective behavior can be formulated, introduce some popular examples of CVs, and present a computational method that generates optimal CVs for certain systems.

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MS26

Markov Processes on Random Networks: Large Population Limits and Fluctuations

We consider time-continuous Markovian discrete-state dynamics on random networks of interacting agents and study their approximation in the form of stochastic differential equations (SDE) for low dimensional collective variables. The collective variables are given by the shares of each discrete state in the system or in certain subsystems. We formally derive the SDEs and elaborate general conditions for the validity of the approximation. We show the application to the so-called voter model on different random graph models like the Erdos-Rnyi model or the stochastic block model. We discuss the quality of the approximation with respect to the different model parameters and provide numerical experiments.

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MS26

Global Stability for McKean-Vlasov Equations on Large Networks

This talk investigates the mean-field dynamics of stochastic McKean (or Kuramoto-type) differential equations with particle interaction patterns described by large network/graph structures. These dynamics are fundamental in a wide range of natural processes such as synchronization phenomena, opinion formation and biological mechanisms. We formulate the limiting McKean-Vlasov equation with a Vlasov interaction term that incorporates the recently developed graph limit theory of graph operators (or graphops). This allows us to cover a wide range of graph structures including dense, sparse and various intermediately dense cases. In this rather general setting, we prove global stability of the homogeneous steady state via entropy methods and provide explicit graph-structure dependent stability conditions and decay rates.

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MS27

Designing Environmental Modifications in Stigmergic Control: a Mathematical Model

Stigmergy is a fundamental mode of information transfer in natural and artificial multi-agent systems, where individual units relay information to others by introducing modifications in the environment. For example, ants release pheromones to guide conspecifics to food sources. Roboticists have tapped into this communication strategy to coordinate large swarms of robots, for example in collective construction tasks. Hitherto, stigmergy has almost exclusively been described through agent-based models implementing individual, behavioral rules. Such an approach is not apt for control-oriented modeling to predict the environmental modifications that are necessary to achieve a desired goal. To address this limitation, we propose a mathematical model for stigmergic control. The model, applicable to large-scale multi-agent systems, is grounded in a continuification of the swarm, whereby we do not study the motion of individual units but consider the overall swarm density that obeys mass conservation, similar to kinetic theories of gases. This procedure allows to establish closed-form solutions of required environmental modifications to achieve target formations for representative interaction kernels between swarm units. We demonstrate our approach in one and two-dimensional problems, considering complex and time-varying target densities for the swarm. Due to its generality, the proposed model paves the way to the implementation of stigmergic control in a broad range of swarms.

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MS27

Control of Nonholonomic Systems to Probability Densities

In this talk, we will explore the set of configurations that can be stabilized in the control of large robot swarms with limited sensing. We analyze the stationary distributions of degenerate diffusion processes associated with control-affine systems, which leads to studying the stability of governing hypoelliptic partial differential equations. First, we consider the case without mean-field terms. We then show how including mean-field interactions can expand the class of stabilizable distributions. Importantly, the mean-field limit allows us to achieve global stability of target configurations, unlike treatments for finite particles. These results provide insights into the fundamental capabilities and limits of decentralized control for emergent collective behaviors in large-scale robotic systems.

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MS27

Linear Quadratic Mean Field Games for Network Populations

This talk will present models and solutions to mean field games with large network couplings and the decomposition method for identifying low-complexity solutions for such problems. More specifically, we will investigate approximate solutions to large-scale linear quadratic stochastic games with heterogeneous network couplings following the graphon mean field game framework. A graphon time-varying dynamical system model is first formulated to study the finite and then limit problems of linear quadratic graphon mean field games. The Nash equilibrium of the limit problem is then characterized by two coupled graphon time-varying dynamical systems. For the computation of solutions, two methods are employed where one is based on fixed point iterations and the other on a decoupling operator Riccati equation; furthermore, two corresponding sets of low-complexity solutions are established based on graphon spectral decompositions.

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MS27

Non-Reciprocal Fokker-Planck Equations for the Shepherding Control Problem: Incorporating Agents Decision Making in the Continuum

The shepherding control problem –where a population of herders has to control the collective dynamics of a population of targets– is a relevant example of how the collective behaviour can solve control tasks. Shepherding behavior is ubiquitous in nature (from sheepdog-flock interactions to opinion dynamics in social networks) and has applications in swarm robotics (e.g., autonomous cleanup of ocean contamination). Yet, its mathematical treatment at the continuum level remains challenging. When targets are repelled by herders, a common shepherding task requires the herders to gather and contain the targets in a goal region by surrounding them; a key element allowing herders success is their ability to decide which target to chase at each time. In this talk, we discuss how to derive Fokker-Planck equations for the densities of herders and targets (ρ^H and ρ^T), incorporating herders' decision-making at the continuum level. The equations present a non-reciprocal coupling in the drift in the dynamics of ρ^H of the form $\phi(\rho^H, \rho^T) = \nabla \cdot [v(x)\rho^H \rho^T]$, where the function $v(x)$ prescribes the task-oriented direction of motion of the herders. This coupling enables the emergence of containment behavior, where ρ^H surrounds and confines ρ^T. The function $v(x)$ can be chosen to accommodate various control objectives and behavioral patterns, making our results relevant for both control theory and statistical physics communities.

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MS28

A Unified Framework for the Analysis of Accuracy and Stability of a Class of Approximate Gaussian Filters for the Navier-Stokes Equations

Bayesian state estimation of a dynamical system utilising a stream of noisy measurements is important in many geophysical and engineering applications. We develop a unified framework for the analysis of several well-known and empirically efficient data assimilation (DA) techniques derived from various Gaussian approximations of the Bayesian filtering schemes for geophysical-type (infinite-dimensional) dissipative dynamics with quadratic nonlinearities. In particular, we consider the model dynamics governed by the two-dimensional incompressible Navier-Stokes equations and observations given by noisy measurements of averaged volume elements or spectral/modal observations of the velocity field. The DA algorithms include the Ensemble Kalman Filter (EnKF) and Ensemble Square Root Kalman Filter (EnSRKF). We establish rigorous results on (time-asymptotic) accuracy and stability of these algorithms with general covariance and observation operators. The derived bounds are given for the limit supremum of the expected value of the L^2 norm and of the $\mathbb{H}^1$ Sobolev norm of the difference between the approximating solution and the actual solution as the time tends to infinity. Our analysis reveals an interplay between the resolution of the observations associated with the observation operator underlying the DA algorithms and covariance inflation and localization which are employed in practice for improved filter performance.

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MS28

Using Data to Inform Models of Nucleus Accumbens Neurons

Since the time of Hodgkin and Huxley, mathematical models of electrical transmission have been used as tools to understand functional properties of different parts of the brain. Here, we focus on a brain region called the nucleus accumbens (NAc) as its ability to integrate diverse information plays a key role in mediating motivated behaviors. Our ultimate goal is to use experimental data to estimate model parameters and assess how model parameters are influenced by various experimental conditions, where the parameter values are associated with characteristics of the experimental data. We model the dynamics of spiking neurons in the NAc using the Izhikevich model by using data assimilation, structural and practical identifiability assessments, parameter estimation, and parameter sensitivity analysis to refine the model. First, we evaluate practical and structural identifiability of parameters to determine whether the parameters can be estimated from the given experimental data. Then, we then show that data assimilation techniques, such as nudging, improve forward prediction of neuronal voltage dynamics. We estimate parameters by minimizing the difference between model predictions and recorded electrophysiological data. Furthermore, by estimating parameters across different experimental groups, we will cluster these parameters to assess neuronal characteristics, facilitating a deeper understanding of how various neural populations respond to stress.

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MS28

Uniquely Recovering Viscosity in 2D NSE from Finitely Many Determining Modes

It is a classical result that, for the Navier–Stokes equations in 2D (with periodic boundary conditions), trajectories on the attractor are determined by finitely many modes (called determining modes). In this talk, we will examine the case where the viscosity is unknown, using a data assimilation technique proposed in [Azouani, Olson, Titi 2014]. We will show that trajectories on the attractor are still determined by finitely many modes, and discuss the problem of recovering the viscosity from the determining modes. We will present theoretical results guaranteeing the solution of this inverse problem, as well as some numerical results that motivated this line of research.

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MS29

Complex Dynamics of Two Interacting Light Fields in Coupled Photonic Crystal Nanocavities

Spontaneous symmetry breaking in optical cavities is the process by which, two optical modes with apparent symmetry break down spontaneously into two non-identical states. Recently, this phenomenon was reported in different configurations of optical resonators with two interacting modes coupled either linearly or nonlinearly. In this work, we study the dynamics of two modes in a photonic crystal dimer, where the configuration of the system favors linear and nonlinear coupling of the two modes, as well as a four-wave mixing-induced nonlinearity. We show that, under these conditions, the system exhibits a wide range of interesting dynamics, including spontaneous symmetry breaking of different types of solutions.

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MS29

Thermo-Optical Excitations and Mixed-Mode Oscillations in An Injected Kerr Microcavity

We study the dynamics of a vertically emitting microcavity containing a Kerr nonlinearity that is subjected to detuned optical injection. To this end, we present an extended model that allows investigation of the influence of cavity heating, which shifts the microcavity resonance and thus the detuning on a slow time scale. As a consequence of this scale separation, we uncover a canard scenario featuring dark and bright excitations, as well as mixed-mode oscillations that can be manipulated by tuning the injection amplitude and frequency. When the microcavity is coupled to a long external feedback loop, subjecting it to strong time-delayed optical feedback, we can examine the additional influence of the time delay on excitability dynamics, as well as the impact of thermal effects on preliminary studies.

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MS29

Disorder-Induced Synchronization in Laser Models

Synchronization is a complex dynamical process in which the rhythms of self-sustained oscillating objects adjust to one another through weak interactions, resulting in collective behavior. Recently, spatial time-delay disorder has been shown to overcome frequency disorder and effectively control synchronization in laser models. In our work, we apply machine learning techniques to identify optimal disorder configurations that achieve synchronization. This approach demonstrates that machine learning can serve as a powerful tool for understanding and exploring the intricate mechanisms underlying disorder-induced synchronization.

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MS30

Exploring Invariant Manifolds in the Presence of Wild Chaos

Wild chaos is a type of robust higher-dimensional chaotic dynamics. One of its defining characteristics is the presence of robust heterodimensional cycles, which include non-transverse intersections between stable and unstable manifolds. The persistence of non-transverse intersections is counter-intuitive: for example, such behaviour in three dimensions necessitates robust intersections between two one-dimensional manifolds. Consequently, such curves must ‘behave’ as if they were a surface, facilitating robust intersections with other one-dimensional manifolds. We focus on a promising potential candidate for a discrete-time dynamical system exhibiting wild chaos, of which there are very few explicit examples. The defining diffeomorphism has dimension three, is volume preserving, and is quadratic with quadratic inverse. We illustrate the emergence of wild chaos in this system by first considering the one-dimensional manifolds of its two fixed points. Indeed, these curves appear to have ‘surface-like’ properties. We show that each fixed point lies in a different hyperbolic set, distinguished by the dimensions of their unstable manifolds. Moreover, the one-dimensional manifolds of these hyperbolic sets intersect to give rise to robust heterodimensional cycles. We also discuss how these manifolds disentangle from each other as a parameter is varied, thereby highlighting specific changes in the manifold geometry that could represent a mechanism to produce wild chaos.

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MS30

Validated Enclosure of Renormalization Fixed Points Using Chebyshev Expansions

We develop a general framework for proving existence, isolation, and stability results for real analytic fixed points of m-th order Feigenbaum-Cvitanovic renormalization operators. The universality properties associated to the fixed points, first discovered by Feigenbaum for m=2 in the context of population dynamics, describe different routes to chaotic behavior in multiple contexts in Mathematics and the physical sciences. We demonstrate the advantages of using Chebyshev expansions for a general approach in this case where the domain of analyticity of the fixed points has a fractal shape enclosing the real and imaginary axis. We present results for renormalization fixed points of order m = 3 through order 10. The method is also applied to fixed points of high critical degree at the origin. Moreover, we reprove the existence of the classical m = 2 Feigenbaum renormalization fixed point, and compute its universal constants up to 500 correct decimal digits. This is joint work with Maxime Breden and Jason Mireles-James.

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MS30

Periodic Forcing of a 3D Conservative Flow with an Invariant 2-sphere of Heteroclinic Connections to Saddle-foci

We consider a one-parameter family of 3D volume-preserving flows of the second order unfolding of the elliptic volume-preserving Hopf-zero bifurcation. This family has two saddle-foci equilibria, whose 2-dimensional stable and unstable invariant manifolds coincide, creating a 2-sphere foliated by spiraling heteroclinic orbits. This sphere is usually referred to as a bubble of stability. We study the effect of a non-autonomous periodic forcing on the splitting of these 2-dimensional invariant manifolds. This perturbation introduces an additional frequency that interacts with the intrinsic frequency associated with the multiplier of the foci. When these frequencies are incommensurable, this interaction results in quasi-periodic behavior in the splitting, which is exponentially small in the unfolding parameter of the Hopf-zero bifurcation. This description naturally lead to some new and open questions related to chaos formation in such systems.

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MS30

RIC-Rolled: Resonant Boundaries of the Chaotic

Scattering Zone in the Restricted Three-Body Problem

We analyze the scattering potential of a test particle originating near the secondary mass in the planar circular restricted three-body problem, aiming to quantify the extent of its possible excursions. To achieve this, we construct an analytical Poincare map—a symplectic twist map—preserving the Hamiltonian structure of the full system. This map reveals a two-dimensional KAM torus that serves as a barrier along a three-dimensional energy surface, forming a boundary to the large three-dimensional chaotic zone which includes the region around the secondary. These tori correspond to the bounding rotational invariant circle (RIC) in the Poincare map, each linked to a specific mean motion resonance. We observe that the semi-major axis of the bounding RICs forms a "staircase" pattern in response to resonances, approximately following a power-law relation with respect to the mass parameter. Moreover, we identify a critical mass parameter near 10^{-5}, beyond which the exterior boundary to the chaotic zone vanishes, indicating that particles in temporary capture orbits near the secondary can escape to infinity.

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MS31

Magnetic Fields with no Hamiltonian Structure

Magnetic fields, under the right conditions, admit a description by a non-autonomous Hamiltonian system. This feature underpins much of the current understanding of magnetic field line topology and consequently, has long shaped the conceptual design of magnetic confinement devices for plasma. In this talk, we delve into the classification of magnetic fields that exhibit a Hamiltonian structure using the monodromy representation of the field. We also explore striking examples of magnetic fields that defy this structure, unveiling unique topological consequences. These non-Hamiltonian magnetic fields not only challenge the traditional perspectives of magnetic fields but also open exciting new avenues for the design of magnetic fields tailored for advanced plasma confinement. This research was conducted in collaboration with David Perrella and David Pfefferle of the University of Western Australia.

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MS31

Coupled Symplectic Maps Describing Transport with Both Nonmonotonic Rotation Number and Shear Flow

Since the work of [1,2] it is known that symplectic nontwist maps, maps that violate Moser's twist condition at a point, posses barriers to transport in the shearless region. Such maps model transport via chaotic advection in zonal flows and magnetic field lines in toroidal plasma devices. In [3] drift wave maps were obtained that describe the motion of charged particles in drift waves, with the possibility of incorporating the effects of both reversed magnetic shear and velocity shear. These maps are parameter drift maps or higher dimensional maps. Barrier formation and transport depending on both magnetic and velocity shearlessness will be described. [1] D. del-Castillo-Negrete and P. J. Morrison, "Chaotic Transport by Rossby Waves in Shear Flow, Phys. Fluids A 5, 948-965 (1993). [2] D. del-Castillo-Negrete, et al., "Area Preserving Nontwist Maps: Periodic Orbits and Transition to Chaos, Physica D 91, 1-23 (1996). [3] W. Horton, et al., "Drift Wave Test Particle Transport in Reversed Shear Profile, Phys. Plasmas 5, 3910-3917 (1998).

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MS31

Nonlinear Dynamics of Energetic Particles in 3D Magnetic Fields

Stellarators are toroidal fusion devices that magnetically confine plasma with 3D magnetic fields. While toroidal symmetry is lost, stellarators can be designed to have hidden symmetries, enabling integrability of the guiding center trajectories. While "precisely quasisymmetric" configurations have been obtained through numerical optimization, stellarator magnetic fields generally have deviations from symmetry that lead to loss of confinement of energetic particles (EPs). There is also the potential for enhanced EP losses due to interaction with background waves, such as Alfvén waves. This talk will provide an overview of the 2 or 2.5 DOF Hamiltonian dynamics of EP guiding center motion. Poincaré sections highlight the non-twist structure due to reversal in the characteristic drift frequency. Diagnostics of phase-space integrability, such as quasi-periodic psuedo-orbits and the weighted Birkhoff average, will be discussed.

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MS31

Hidden Lower-Dimensionality of Excellent Quasisymmetric Magnetic Fields and itsImplications

Quasisymmetry (QS) is a hidden symmetry of the magnetic field strength, B, that confines charged particles effectively in a 3D toroidal plasma equilibrium. Here, we show that QS has a deep connection with solitons. We uncover a hidden lower dimensionality of B on a magnetic flux surface, which could make stellarator optimization schemes significantly more efficient. Our approach elucidates why the magnetic shear is low in configurations with excellent QS. We present three independent approaches to demonstrate that quasisymmetric B is described by integrable systems such as Korteweg-de Vries (KdV) and Gardner's equation. A weakly nonlinear multiscale perturbation theory approach highlights magnetic shear's crucial role in QS. A non-perturbative approach based on ensuring the single-valuedness of B directly leads to its Painleve property, which is shared by the KdV equation. Our third machine learning approach, trained on a large dataset of numerically optimized quasisymmetric stellarators, robustly recovers the KdV (and Gardner's) equation from the data. Finally, we deduce a maximum quasisymmetric toroidal volume and verify it for the Landreman-Paul precise quasi-axisymmetric (QA) stellarator configuration. We discuss the strong constraints this upper bound imposes on flux surface shapes and the possible impact on divertor and coil designs. Supported by the U.S.DoE Grant No. DE-FG02-86ER53223, the Simons Foundation/SFARI (560651, AB), and DoE Contract No DEAC02-09CH11466.

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MS32

Hypocoercivity for Nonlinear SPDEs

Motivated by problems from Industrial Mathematics we further developed the concepts of hypocoercivity. The original concepts needed Poincar inequalities and were applied to equations in linear finite dimensional spaces. Meanwhile we can treat equations in manifolds or even infinite dimensional spaces. The condition giving micro- and macroscopic coercivity we could relax from Poincar to weak Poincar inequalities. In this talk an overview and many examples are given.

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MS32

Stabilization by Rough Noise for an Epitaxial Growth Model

In this article we study a model from epitaxial thin-film growth. It was originally introduced as a phenomenological model of growth in the presence of a Schwoebbel barrier, where diffusing particles on a terrace are not allowed to jump down at the boundary. Nevertheless, we show that the presence of arbitrarily small space-time white noise due to fluctuations in the incoming particles surprisingly eliminates all non-linear interactions in the model and thus has the potential to stabilize the dynamics and suppress the growth of hills in these models.

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MS32

It-Ventsel Formula for Semimartingales with Jumps: Applications on Decomposition of Flows

We propose a new interpretation and proof of the It-Ventsel-Kunita formula for Marcus equations driven by semimartingales with jumps. We apply the formula for two kinds of geometrical decomposition of stochastic flows of semimartingales with jumps: a coordinate preserving decomposition (along complementary foliations) and a non-linear Iwasawa decomposition for flows in a Riemannian manifold.

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MS32

Effective Dynamics of Interfaces for Nonlinear Spdes Driven by Multiplicative White Noise

In the present work, we investigate the dynamics of infinite-dimensional stochastic partial differential equations (SPDEs) with multiplicative white noise. We derive the effective equation on the approximate slow manifold in detail by utilizing a finite-dimensional stochastic ordinary differential equation (SDE) that describes the motion of interfaces. In particular, we verify the equivalence between the full SPDE and the coupled system under small stochastic perturbations. We use sophisticated large deviation techniques to analyze stochastic stability and show that solutions stay close to the slow manifold for a very long time with high probability via asymptotic estimates on the exit time. Furthermore, we apply our results to multiple equations, illustrated with practical examples concerning dynamical stability.

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MS33

Brood Pile Geometry and Collective Energetic Regulation in Ant Colonies

The metabolism of ant colonies scales with colony size analogously to how we usually think about metabolism for individual organisms, namely that energy use increases at a sublinear rate with mass, a relationship known as Kleibers law. This observation motivates the view of ant colonies as so-called superorganisms, which perform tasks and regulate resource use collaboratively among all the individuals for the good of the collective much like the cells of an organism. How ants achieve this collective energetic regulation in practice is not fully understood, but must include how both foraging and brood care are executed, since these are primary tasks performed in all ant colonies. Working from experimental data collected from a Tetramorium species, we have explored this question from the perspective of the environmental geometry initiated by the ants themselves, that is, the shape of the brood pile created by brood care workers. We will discuss the scaling relationships between colony size, brood number, and brood pile surface area and volume, and how this relates to efficiency in terms of brood care. Furthermore, we investigate how brood pile geometry affects interactions between brood care workers and foraging ants, which links directly to the colonys metabolism through social activation mechanisms captured by an agent-based model.

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MS33

Capelin, a Probe for Climate

Due to its responsiveness to changes in the marine environment, G. Rose suggested in 2005 that the capelin, a small pelagic fish that is key to the ecology and fisheries of the North Atlantic, could be seen as a canary in the coalmine to detect signals of changes in the Arctic and sub-Arctic Ocean. We describe the historical data that make possible a quantitative assessment of the geographical shift capelin migrations and spawning grounds undergo, with increasing temperature, and the time it takes to make these shifts long-lasting. Direct measurements made in the fall expeditions of Icelands Marine and Freshwater Research Institute along the East Coast of Greenland, and the Copernicus database of the European Union, are used to examine the evolution of the returning Atlantic water (from Svalbard) that is forming a warmer and saltier boundary current under the colder and fresher East Greenland polar current. The returning Atlantic water (RAW) has a temperature range (1 to 4 degrees Centigrade) suitable for feeding migrations of the capelin. A trend emerges, both in the direct measurements and in Copernicus data, showing that the returning Atlantic water (RAW) current may reach Greenlands major northeastern glacier streams, draining the bulk of the Northeastern Greenland Ice Sheet (GrIS) in the near future. We use both the capelin data and the Copernicus simulations to predict that this may happen in less than 12 years.

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MS33

Detecting Coupling in Collective Dynamics Via Kalmans Observability

Detecting coupling in network dynamical systems from time-series is an open problem in the physics of complex systems. In this work, we tackle this issue from a control-theoretic perspective by drawing inspiration from Kalman's notion of observability, which describes the extent to which the internal states of a system can be estimated from its external states. In this talk, we argue that a direct coupling between two units, $X \rightarrow Y$, corresponds to X being an internal state from the measurement of Y. By invoking the equivalence between the notions of observatory and detectability, we pursue the discovery of internal states through the use of a detection matrix that is assembled from raw observations. We illustrate this approach through a series of analytically tractable examples of collective dynamics, showcasing how it overcomes some of the limitations of state-of-the-art methods.

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MS33

A Continuous Model of Raft Formation Through Pilus-driven Motility

Some bacteria can move along surfaces by extending one or more "pili", microscopic grappling hooks that are forcefully retracted. This results in a random walk in which the angle between the major axis of the cigar-shaped microorganisms and their velocity remains small. Because of the excluded volume, bacteria tend to align in areas of high density which, in turn, can lead to "rafts", semi-permanent patches of densely packed individuals. Such rafts can be the precursor to biofilm formation, and we would like to study and control this process. Agent-based modelling is challenging due to the large number of agents needed to model rafts. Instead, we formulated a 2+1D continuum model that takes the form of a non-local, non-linear PDE. We will present this model and some preliminary simulation results.

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MS34

Breathers and Mixed Oscillatory States Near a Turing-Hopf Instability in a Twocomponent Reactiondiffusion System

Numerical continuation is used to study the interaction between a finite wave number Turing instability and a zero wave number Hopf instability in a two-species reactiondiffusion model of a semiconductor device. The model admits two such codimension-two interactions, both with a subcritical Turing branch that is responsible for the pres-

ence of spatially localized Turing states. The Hopf branch may also be subcritical. We uncover a large variety of spatially extended and spatially localized states in the vicinity of these points and by varying a third parameter show how disconnected branches of time-periodic spatially localized states can be zipped up into snaking branches of time-periodic oscillations. These are of two types: a Turing state embedded in an oscillating background, and a breathing Turing state embedded in a non-oscillating background. Stable two-frequency states resembling a mixture of these two states are also identified. Our results are complemented by direct numerical simulations. The findings explain the origin of the large multiplicity of localized steady and oscillatory patterns arising from the Turing-Hopf interaction and shed light on the competition between them.

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MS34

Localized Dissipative Vortices in Chiral Nematic Liquid Crystal Cells

Solitary waves and solitons have been fundamental in understanding nonlinear phenomena and emergent particle-type behaviors in out-of-equilibrium systems. This dynamic phenomenon has been essential to comprehending the behavior of fundamental particles and establishing the possibilities of novel technologies based on optical elements. Dissipative vortices are topological particle-type solutions in vectorial field out-of-equilibrium systems. These states can be extended or localized in space. The topological properties of these states determine their existence, stability properties, and dynamic evolution. Under homeotropic anchoring, chiral nematic liquid crystal cells are a natural habitat for localized vortices or spherulites. However, chiral bubble creation and destruction mechanisms and their respective bifurcation diagrams are unknown. We propose a minimal two-dimensional model based on experimental observations of a temperature-triggered first-order winding/unwinding transition of a cholesteric liquid crystal cell and symmetry arguments and investigate this system experimentally. This model reveals the main ingredients for the emergence of chiral bubbles and their instabilities. Experimental observations have quite fair agreement with the theoretical results. Our findings are a starting point for understanding dissipative particles' existence, stability, and dynamical behaviors with topological properties.

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MS34

Vegetation Traveling Pulses Enhance Ecosystem Resilience

The emergence and dynamics of localized structures play a central role in the resilience of ecosystems. In this talk, I will present our study of a minimal model where traveling pulses–localized vegetation structures–emerge as a key mechanism for enhancing ecosystem resilience. These structures arise from the interaction between positive feedback and toxin-mediated negative feedback and bear strong similarities to excitable pulses observed in physical systems. Using bifurcation analysis, we reveal the existence and stability of localized solutions, with their bifurcation structure organized by codimension-2 saddle-loop and T-point bifurcations. Additionally, we explore related dynamical regimes such as defect turbulence and spirals, which contribute to the richness of the system's behavior. These non-stationary solutions persist in parameter ranges where homogeneous systems would otherwise collapse, offering stability against environmental stress. Our findings emphasize the significance of traveling pulses and other spatiotemporal structures in maintaining ecosystem productivity and resilience, drawing direct parallels with the dynamics of physical systems near critical transitions like Hopf bifurcations.

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MS34

Exploring the Free Energy Landscape of Block Copolymer Nanoparticles: A Nonautonomous Approach to Targeted Morphologies

Block copolymers can form nanoscale particles exhibiting diverse three-dimensional morphologies, driven by particle shape and internal microphase separation. A suitable free energy allows a coupled system of the Cahn-Hilliard model to emerge as a gradient system. However, it remains unclear where specific target morphologies, like Platonic solids, lie within the free energy landscape. Here, I present an approach that adjusts time constants during the evolution of the solution to guide it toward these exotic shapes. Using a simplified one-dimensional Cahn-Hilliard equations, I will demonstrate (1) the structure of the free energy's global saddle network, (2) the classification of minimizers as path-dependent destinations, and (3) the impact of time constants parameters on two unknown functions. This approach is related to rate-tipping phenomena; however, it leverages this effect constructively to achieve targeted outcomes, rather than leading to catastrophic changes.

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MS35

Learning Transfer Operator Dynamics on Latent Spaces

The transfer operator method allows us to convert complex, nonlinear dynamical systems into linear representations that are simpler to analyse. While the spectrum of these operators may contain important insights into system predictability and emergent behaviour, approximating transfer operators from data can be challenging. We address this problem through the lens of general operator and representational learning, in which we approximate the action of transfer operators on infinite-dimensional spaces using tractable finite-dimensional forms. Specifically, we machine learn orthonormal, locally supported basis functions that are tailored to the system dynamics. These learned basis functions and dynamics then serve to compute accurate approximations of the transfer operator's eigenpairs. Our approach offers a promising direction for robust approximation of transfer operators, particularly in high-dimensional systems where traditional numerical methods may become computationally intractable.

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MS35

Data-Driven Methods for Approximating the Transfer Operator

The spectrum of the transfer and Koopman operators of a dynamical system reveal useful information about the dynamics of the system, such as identifying cycles and their frequencies. Recently there has been a surge in popularity for methods for approximating these operators from measurement data without necessarily knowing the underlying equations of the system. In this presentation, we look at two such methods for constructing approximations to the transfer operator. Both methods involve several parameters and the accuracy of their output depends on the values chosen for these parameters. For a variety of systems, we compare the results obtained using the two methods and investigate ways of choosing parameter values which yield good results.

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MS35

Measure-Theoretic Time-Delay Embedding

The celebrated Takens' embedding theorem provides a theoretical foundation for reconstructing the full state of a dynamical system from partial observations. However, the classical theorem assumes that the underlying system is deterministic and that observations are noise-free, limiting its applicability in real-world scenarios. Motivated by these limitations, we rigorously establish a measure-theoretic generalization that adopts an Eulerian description of the dynamics and recasts the embedding as a push-forward map between probability spaces. Our mathematical results leverage recent advances in optimal transportation theory and the Wasserstein geometry. Building on our novel measure-theoretic time-delay embedding theory, we have developed a new computational framework that forecasts the full state of a dynamical system from time-lagged partial observations, engineered with better robustness to handle sparse and noisy data. We showcase the efficacy and versatility of our approach through several numerical examples, ranging from the classic Lorenz-63 system to large-scale, real-world applications such as NOAA sea surface temperature forecasting and ERA5 wind field reconstruction.

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MS35

Dynamics Stable Learning by Invariant Measure for Chaotic Systems

Learning dynamics from dissipative chaotic systems is notoriously difficult due to their inherent instability. Fortunately, many of these systems exhibit ergodicity and an attractor: a compact and highly complex manifold, to which trajectories converge in finite-time, that supports an invariant measure, i.e., a probability distribution that is invariant under the action of the dynamics, which dictates the long-term statistical behavior of the system. In this talk we present a new framework that targets learning the invariant measure as well as the dynamics, along with a tractable and sample-efficient regularization that can be used with any existing learning method. We will showcase the rationale of this approach, it properties and its performance in a set of benchmarks, ranging from ODE systems to 2-dimensional turbulent problems.

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MS36

Singular Basins and Tipping in a Model of Adaptive Phase Oscillators

We consider a networked model of adaptive phase oscillators akin to θ-neurons, namely

$$\begin{aligned} \dot{\varphi}_i &= \omega_i + \mu - \sin\varphi_i + \frac{\kappa}{N}\sum_{j=1}^{N}\sin(\phi_j - \phi_i), \\ \dot{\mu} &= \epsilon(-\mu + \eta(1 - X)), \end{aligned} \tag{1}$$

where $X = \frac{1}{N}\sum_{j=1}^{N}\sin(\varphi_j + \alpha)$. We first describe the dynamics of one oscillator and show how for some parameter values, and due to the timescale given by the small parameter $\epsilon \ll 1$, a stable equilibrium point, and a stable limit cycle organize the dynamics with the latter having a singular basin of attraction. We then describe how this singular basin of attraction leads to tipping. More precisely, depending on the rate of change of the parameter ω, a trajectory may converge either to the stable equilibrium point or to the limit cycle. Finally, we show how these observations extend to the network model.

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MS36

”R-double-tipping”: Rate-induced Collapse in Three-time-scale Ecological Models

In this talk, we study rate-induced tipping (r-tipping) phenomena in a three-time-scale tri-trophic food-chain model, subject to parameter forcing evolving on the slowest time scale. Focusing on Geometric Singular Perturbation Theory (GSPT) methods - communicated through many animations - we introduce what has been termed R-double-tipping, a novel phenomenon where r-tipping occurs across all three timescales. Following this, we explore the direct consequences of tipping across multiple time scales, including purely rate-induced extinction events and a paradoxical rescue mechanism that occurs along the R-double-tipping boundary.

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MS36

Uncertainty Quantification for Overshoots of Tipping Thresholds

Many subsystems of the Earth are at risk of undergoing abrupt transitions from their current stable state to a drastically different, and often less desired, state due to anthropogenic climate change. One common mechanism for tipping to occur is via forcing a nonlinear system beyond a critical threshold that signifies self-amplifying feedbacks inducing tipping. However, previous work has shown that it is possible to briefly overshoot a critical threshold and avoid tipping. For some cases, the peak overshoot distance and the time a system can spend beyond a threshold are governed by an inverse square law relationship. In the real world or complex models, critical thresholds and other system features are highly uncertain. In this presentation, we look at how such uncertainties affect the probability of tipping from the perspective of uncertainty quantification. We show the importance of constraining uncertainty in the location of the critical threshold and the linear restoring rate to the systems stable state in a simple box model for the Atlantic Meridional Overturning Circulation (AMOC). Thereby, we highlight the need to constrain the highly uncertain diffusive timescale within the box model to reduce tipping uncertainty for overshoot scenarios of the AMOC.

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MS37

The Instabilities of 2-D Periodic Traveling Water Waves

Using the framework due to Nicholls and Reitich, we compute 2-D traveling solutions to the classical water wave problem. The exact reformulation of the classical surface water wave problem due to Ablowitz, Fokas, and Musslimani then provides a convenient framework to examine the spectral stability of these waves. We consider zero-average perturbations and linearize about the computed solutions, in line with the works of Deconinck and Oliveras on 1-D waves. The generalized Fourier-Floquet-Hill method allows us to efficiently and accurately compute the stability spectra of these waves. We examine the instabilities of 2-D waves in both shallow and deep water, comparing our findings to the results for longitudinal and transverse perturbations of 1-D waves.

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MS37

The Instabilities of Stokes Waves

I will provide an overview of relevant results (analytical, asymptotic, computational) in the literature, both classical and more recent on the instabilities of water waves. I will emphasize especially results for steep waves, near the extreme 120 degree wave.

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MS37

Exact Periodic Solutions of the Generalized Constantin-Lax-Majda Equation and Dynamics of Their Poles

We present several exact solutions of the generalized Constantin-Lax-Majda equation with dissipation $\omega_t = -au\omega_x + \omega\mathcal{H}\omega - \nu\Lambda^\sigma(\omega), u_x = \mathcal{H}\omega$, where $\widehat{\Lambda^\sigma} = |k|^\sigma$, both for the problem on the circle $x \in [-\pi, \pi]$ and the real line. We analyze these solutions from the stand point of complex pole singularities and their motion in the complex plane and find conditions for finite time collapse in these solutions for advection parameter $a = 0, 0.5$, dissipation coefficient $\nu \geq 0$ and dissipation power $\sigma = 0, 1$ values. These solutions are also compared to a global-in-time well-posedness theory.

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MS37

Spatially Quasi-Periodic Water Waves

For linearized gravity-capillary waves, two periodic waves with different wavelengths may travel at the same speed. If the ratio of their wavelengths is irrational, the motion of their superposition becomes spatially quasi-periodic. We present a framework for computing and studying one-dimensional spatially quasi-periodic water waves, and we will also discuss an approach to extend this study to two-dimensional waves. This talk is based on joint work with Jon Wilkening and David Nicholls.

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MS38

Bayesian Parameter Inference in Agent-based Models of Zebrafish Patterns Using TDA

Collective behavior of individual agents is present across biological systems, as in the case of migrating cells during development, the formation of animal skin patterns, and bird flocking. Agent-based models offer a flexible and natural framework for capturing these pattern formation processes. However, inferring the parameters in such models poses significant challenges. We demonstrate that combining topological data analysis (TDA) with approximate approximate Bayesian computation (AABC) is a computationally feasible approach to addressing these challenges. In our study, we focus on an existing agent-based model of pattern formation in zebrafish skin, and we show how to estimate parameters in this complex, stochastic model. We also discuss how parameter identifiability depends on various choices in our pipeline, such as how to summarize and weight topological information, and what time points to use when estimating parameters involved in pattern formation.

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MS38

Learning and Discerning Multiple Cell Sub-Populations in Wound Healing Experiments Using Weak-Form Equation Learning

In the field of equation discovery, the Weak form Sparse Identification of Nonlinear Dynamics (WSINDy) methodology has shown to be computationally efficient for identifying the governing equations of complex systems from noisy data. In the context of cell migration, the relevant dynamical models are 1st-order and 2nd-order interacting particle systems (IPS). In the 1st-order case, WSINDy has shown to successful infer interaction rules by leveraging mean-field theory and associated nonlocal PDEs. For 2nd-order models, heterogeneous interaction rules have been considered, and a joint model selection and classification method to both learn governing IPS equations and sort individuals into distinct interaction rule classes has been developed. The present talk will demonstrate that these weak-form-based IPS discovery techniques may be used to efficiently identify cell heterogeneity and test key assumptions employed to explain wound closure, such as the leader-follower dichotomy.

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MS38

Forecasting and Predicting Stochastic Agent-Based Model Data with Biologically-Informed Neural Networks

Collective migration is an important component of many biological processes. Agent-based models (ABMs) are often used to model collective migration, but it is challenging to thoroughly predict these models behavior through parameter space due to their random and computationally intensive nature. Modelers often coarse-grain ABM rules into mean-field differential equation (DE) models. These DE models are fast to simulate, they suffer from poor (or even ill-posed) ABM predictions in some regions of parameter space. In this work, we describe how biologically-informed neural networks (BINNs) can be trained to learn interpretable BINN-guided DE models capable of accurately predicting ABM behavior. In particular, we show that BINN-guided partial DE (PDE) simulations can (1) forecast future spatial ABM data not seen during model training, and (2) predict ABM data at previously-unexplored parameter values. This latter task is achieved by combining BINN-guided PDE simulations with multivariate interpolation. We demonstrate our approach using three case study ABMs of collective migration that imitate cell biology experiments and find that BINN-guided PDEs accurately forecast and predict ABM data with a one-compartment PDE when the mean-field PDE is ill-posed or requires two compartments. This work suggests that BINN-guided PDEs allow modelers to efficiently explore parameter space, which may enable data-driven tasks for ABMs, such as estimating parameters from experimental data.

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MS38

A Unified Approach to Parameter Identifiability, Parameter Estimation, and Model Reduction: Sloppihood

Parameter non-identifiability is a major impediment when interpreting experimental or observational data using mathematical models. Current approaches for diagnosing and resolving parameter non-identifiability and model reduction (symbolic methods, profile likelihood analysis, sloppiness) entail certain advantages and disadvantages, and these three approaches are rarely combined. We discuss a general approach for diagnosing and resolving parameter non-identifiability by uniting the strengths of existing approaches and avoiding potential pitfalls. The new approach, called *sloppihood*, enables the discovery and ranking of practically identifiable parameter combinations without symbolic computation. Ranked parameter combinations can be used as *interest parameters* in a *Profile-Wise Analysis* framework for practical identifiability, uncertainty analysis and model reduction based on profile likelihood. We present open-source Julia software illustrating how to implement this new methodology across a range of mathematical models that describe observational data.

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MS39

Robustness of Feedback Control for SIQR Epidemic Model Under Measurement Uncertainty

We study a four state continuous time control system that models susceptible, infected, isolated, and recovered (SIQR) populations in the presence of an infectious disease to which immunity is long lasting, and whose three feedback controls represent isolation, contact regulation, and vaccination. The model contains four time-varying uncertainties. One uncertainty models uncertain immigration into a population. The other three represent uncertainties in the measurements of the susceptible, infected, and isolated population counts that are used in the feedback controls. We study the model using input-to-state stability (ISS), which is a generalization of asymptotic stability that is commonly used in control engineering to quantify the effects of uncertainty, and which coincides with asymptotic stability when the uncertainties are zero. Using a strict Lyapunov function construction method from a recent paper by H. Ito, M. Malisoff, and F. Mazenc (Ito et al. Feedback control of isolation and contact for SIQR epidemic model via strict Lyapunov function, 2023), we provide two ISS results that quantify the robustness of the feedback control with respect to the four uncertainties. We illustrate the effectiveness of our approach in simulations, using parameter values from the COVID-19 pandemic.

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MS39

An Analysis of the Dynamics in a Mathematical Model Incorporating Environmental Virus Concentration

This study presents a mathematical model designed to provide insight into the dynamics of infectious disease transmission within human populations. The model incorporates essential elements such as imperfect vaccination coverage and transmission driven by viral particles present in the environment. We begin by presenting the mathematical model and examining the fundamental attributes of its solutions. A significant aspect of the model is incorporating a response function, which elucidates the impact of environmental viral concentrations on the transmission process. This function, dependent on an integer parameter $n \geq 1$, plays a crucial role in determining the occurrence of backward bifurcation within the system. Our analysis reveals the presence of backward bifurcations, where an endemic equilibrium can exist even when the basic reproduction number R_0 is less than one. Furthermore, we demonstrate that multiple endemic equilibria can arise under specific conditions. Lastly, we explore potential model extensions to account for the influence of climate change on disease transmission dynamics.

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MS39

Bifurcations in Fear Behaviour Impact Final-Size in a Disease Epidemic

We explore a mathematical model of disease transmission with a fearful compartment. Susceptible individuals become afraid by either interacting with individuals who are already afraid or those who are infected. Individuals who are afraid take protective measures via contact reductions to reduce risk of transmission. Individuals can lose fear naturally over time or because they see people recovering from the disease. We consider two scenarios of the model, one where fear is obtained at a slower rate than disease spread and one where it is comparable. In the former we show that behavioural change cannot impact disease outcome, but in the latter, we observe that sufficient behavioural intervention can reduce disease impact. However, response to recovery can induce a bifurcation where contact reduction cannot mitigate disease spread. We identify this bifurcation and demonstrate its implication on disease dynamics and final size.

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MS40

Temperature Effects on Seizures

We present a computational model of networked neurons developed to study the effect of temperature on neuronal synchronization in the brain in association with seizures. The network consists of a set of chaotic bursting neurons surrounding a core tonic neuron in a square lattice with periodic boundary conditions. Each neuron is reciprocally coupled to its four nearest neighbors via temperature dependent gap junctions. Incorporating temperature in the gap junctions makes the coupling stronger when temperature rises, resulting in higher likelihood for synchrony in the network. Raising the temperature eventually makes the network elicit waves of synchronization in circular ripples that propagate from the center outwardly. We suggest this process as a possible underlying mechanism for seizures induced by elevated brain temperatures.

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MS40

Plastic Neural Network with Transmission Delays and the Equivalence Between Function and Structure

The brain is formed by cortical regions that are associated with different cognitive functions. Neurons within the same region are more likely to connect than neurons in distinct regions, making the brain network to have characteristics of a network of subnetworks. The values of synaptic delays between neurons of different subnetworks are greater than those of the same subnetworks. This difference in communication time between neurons has consequences on the firing patterns observed in the brain, which is directly related to changes in neural connectivity, known as synaptic plasticity. In this work, we build a plastic network of HodgkinHuxley neurons in which the connectivity modifications follow a spike-time dependent rule. We define an internal-delay among neurons communicating within the same subnetwork, an external-delay for neurons belonging to distinct subnetworks, and study how these communicating delays affect the entire network dynamics. Our results show how synaptic delays and plasticity work together to promote the formation of structural coupling among the neuronal subnetworks. We conclude that plastic neuronal networks are able to promote equivalence between function and structure meaning that topology emerges from behavior and behavior emerges from topology, creating a complex dynamical process where topology adapts to conform with the plastic rules and firing patterns reflect the changes on the synaptic weights.

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MS40

Exploring Astrocytic Excitability: the Impact of Morphology and Neurotransmitter Inputs on Calcium Dynamics

Astrocytes are complex cells that play a key role in brain function, exhibiting intracellular calcium signals in response to neurotransmitter stimulation. These signals depend on calcium and IP3 dynamics, which are influenced by cell morphology and neurotransmitter type. However, the interaction between these factors is not fully understood. Here, we present a two-variable model of an astrocytic process that explores how process radius and neurotransmitter type affect intracellular calcium and IP3 dynamics. Phase-plane analysis shows that process radius acts as an excitability threshold, with thicker compartments producing calcium signals and thinner ones increasing IP3 without triggering signals. The model also reveals distinct responses to glutamatergic and dopaminergic inputs, with glutamate having a stronger effect. When both inputs are combined, dopamine enhances glutamate's influence. This simplified model effectively captures astrocyte behavior and enables further study using dynamical systems approaches.

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MS40

Modelling *C. elegans* Processing and Response to Temperature Gradients

The dynamical mechanisms underlying thermoreception in the nematode C. elegans are studied with a mathematical model for the amphid finger-like ciliated (AFD) neurons. The equations, equipped with Arrhenius temperature factors, account for the worms thermotaxis when seeking environments at its cultivation temperature, and for the AFDs calcium dynamics when exposed to both linearly ramping and oscillatory temperature stimuli. Calculations of the peak time for calcium responses during simulations of pulse-like temperature inputs are consistent with known behavioral time scales of C. elegans. Based on our results it is possible to suggest a potential mechanism by which AFD responds to heat.

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MS41

Finding Hopf Bifurcation Islands and Identifying Thresholds for Success Or Failure in Oncolytic Viral Therapy

In this work we introduce the concept of a "Hopf bifurcation Island". The Hopf bifurcation island is a closed bounded region in the parameter space whose boundary consists of Hopf bifurcation points. We will show that the "size" of Hopf Island determines the minimum doubling time of oscillation amplitude and we prove that small Islands can imply very slowly growing oscillatory solutions. As an application we model the interactions between cancer cells and viruses during oncolytic viral therapy. We identify the one dimensional and two dimensional Hopf islands for this model. We depict fast and slow dynamics for this model; there exists a two-dimensional globally attracting surface that includes a stable periodic solution. All solutions with positive initial conditions rapidly approach this two-dimensional attracting surface, and the trajectories on the attracting surface slowly tend to the periodic solution. Moreover, we identify parameter regions that yield treatment failure or success.

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MS41

Uncovering Unstable Blowup in PDEs Through An Exploration of Invariant Manifolds

When a PDE that generates an analytic semiflow blows up, its solutions may be continued in complex time around the singularity producing a branched Riemann surface. The work Cho et al. [*Jpn. J. Ind. Appl. Math.* 33 (2016): 145-166] investigated this phenomena for the quadratic heat equation $u_t = u_{xx} + u^2$ for $x \in \mathbb{T}$. Furthermore, when solutions are continued for purely imaginary time one effectively obtains a nonlinear Schrdinger equation (NLS) $iu_t = u_{xx} + u^2$, and the authors conjectured that this NLS is globally well-posed for real initial data. We identify initial data whose numerical solution blows up, in contradiction of this conjecture. Furthermore, the set of real initial data which blows up under the NLS dynamics appears to occur on a codimension-1 manifold, and we conjecture that it is precisely the stable manifold of the zero equilibrium for the nonlinear heat equation. We apply the parameterization method to study the internal dynamics of this manifold, offering a heuristic argument in support of our conjecture. The solution exhibits self-similar blowup and potentially nontrivial self-similar dynamics, however the proper scaling ansatz remains elusive.

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MS41

Switching Between Multiple Invariant Sets in Neuronal-Inspired Network Dynamics

Experimental neuroimaging evidence, from functional MRI to EEG measurements, reveals that the human brain exhibits switching between different synchrony activity patterns and functional networks over time. These synchrony patterns evolve spatiotemporally on a network, encompassing different levels of synchrony across nodes. The transitions between synchrony patterns raise a central question: How do brain networks have the ability to switch between various synchrony patterns? Motivated by recent advances in multilayer modeling within network neuroscience, we propose a duplex network approach, where the top layer is directly coupled to a reference bottom layer that undergoes transitions between synchrony patterns. Each synchrony pattern corresponds to a cluster state lying on one of the multiple invariant sets under the bottom or duplex dynamics. In isolation, the bottom layer remains in a particular pattern; however, in the presence of the top layer, the network displays spatiotemporal switching. From a dynamical systems perspective, the top layer, in conjunction with inter-layer coupling, acts as a symmetry breaker, governing the bottom layer and limiting the allowed symmetry-induced patterns. These findings are validated through numerical simulations in coupled Hindmarsh-Rose oscillators.

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MS41

What Is the Graph of a Dynamical System?

Frequently we describe a dynamical system in terms of its attractors, but that can leave out important information about unstable invariant sets. A directed graph of a dynamical system is a picture that outlines how the various invariant sets of a dynamical system are related. The simplest example is of the logistic map. Its graph can be extremely complicated. There are dynamical systems with infinitely many attractors, and we want to know how these are dynamically related.

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MS42

Computing Cardiac Electrophysiology from Tissue Mechanics

In this talk, I will discuss computational and experimental methods with which we can better understand the relationship between cardiac electrophysiology and tissue mechanics. The heart's contractions are governed by nonlinear waves of electrical excitation, which propagate rapidly through the heart's muscle and cause heart muscle cells to contract. The global electrical wave patterns are reflected in the deformations of the heart muscle and we recently demonstrated that simulated electrical scroll wave patterns can be computed from the deformation of the ventricles using deep learning. In this talk, I will expand on these findings and explore whether we can still compute electrical waves from mechanical deformation when the two phenomena become dissociated.

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MS42

Density Estimation for Cardiac Electrophysiological Models Using Latent Deep Learning Networks

Mechanistic modeling has been used to describe a variety of biological phenomena. Given input parameters, these models can be simulated to generate predictions about the behavior of the biological systems they describe. The inverse problem involves using experimental data to infer the model parameters. Some issues that arise when attempting to solve such inverse problems stem from nonlinearities, noisy datasets, and inadequate models that cannot fully capture the dynamics of the biological process. Additionally, accurately identifying model parameters from experimental data can be an ill-posed problem due to parameter identifiability issues, where different sets of parameters may produce similar model outputs. This often leads to overfitting or underfitting, making the predictions unreliable. Further, many traditional parameter estimation methods involve loss functions calculated directly on the raw data, which can exacerbate the aforementioned issues. Hybrid models, which combine mechanistic models with data-driven machine-learning approaches are gaining popularity. For instance, neural networks can be used to learn components of a biological system that are difficult to model mechanistically, while maintaining the interpretability provided by mechanistic models. In this work, we propose implementing feature-driven model inversion approaches that use novel deep learning architectures, such as diffusion models, to answer pressing questions about cardiac models.

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MS42

Deep Learning Chaoticity Analysis of Frog Heart Time Series

Real data usually has drawbacks, such as noisy and short recordings, which can cause imprecise results when performing a chaoticity analysis with classic tools as Lyapunov exponents. In addition, when dealing with large datasets, human intervention is not feasible, and an automatic algorithm is needed. When working with theoretical dynamical systems, Deep Learning performs quite well in dynamics classification. In this presentation, we propose a Deep Learning chaoticity algorithm to analyze the dynamical behavior of biological time series. The methodology is applied to experimental data from frog heart. This is joint work with Roberto Barrio, Flavio H. Fenton, Molly Halprin, Conner Herndon, and Mikael Toye.

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MS42

Sparse Identification of Nonlinear Dynamical Systems: Applications to Cardiac Electrophysiology

Modeling cardiac action potentials (APs) presents a challenge due to the hearts physical complexity and ability to generate chaotic spiral wave behavior. As a result, electrophysiological cardiac models continue to proliferate, each with varying strengths and weaknesses. Sparse Identification of Nonlinear Dynamics (SINDy) is a sparse regression method that shows promise for fitting realistic models to cardiac AP data. SINDy relies on carefully selected a-priori function libraries from which to draw in order to regress on a system of PDEs. In this presentation, I analyze the effectiveness of SINDy in fitting simple, analytical cardiac models, such as FitzHugh-Nagumo, to synthetic and experimental data using a minimal set of modifications. In addition, practical findings on the best use of optimizers, function libraries, and more are presented using existing

SINDy libraries such as PySINDy along with custom implementation(s).

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MS43

Model Reduction for Multiscale Dynamics on Networks

Consider a complex system consisting of a large number of interacting agents, coupled through pairwise interactions with nonhomogeneous weights. Simulating the dynamics and identifying patterns of collective behavior can become computationally expensive, particularly as the system size grows, making most of the related algorithms unscalable. In this talk, I propose a model-reduction framework that transforms heterogeneous interacting particle systems into multi-community mean-field models by accounting for the network community structures for reduction. I will also introduce two structure-preserving numerical methods for solving these reduced mean-field equations.

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MS43

Stochastic Simulation Algorithm for Spreading Dynamics on Adaptive Time-Evolving Networks

Mathematical modelling of infectious disease spreading on temporal networks has recently gained popularity to understand the interplay between social dynamics and epidemic processes. The spread of a disease is influenced by properties of the network structure, such as clustering, and by human behaviour, like social distancing and increased hygiene, which can alter network properties. These changes are usually triggered by macroscopic dynamics of the outbreak, such as rising number of reported cases. While analytic solutions for these systems can usually not be obtained, numerical studies through exact stochastic simulation have remained infeasible for large, realistic systems. We introduce a rejection-based stochastic sampling algorithm with high acceptance probability ('high-acceptance sampling'; HAS), tailored to simulate disease spreading on adaptive networks. We show that HAS is exact and can be multiple orders faster than Gillespie's algorithm. While its computational efficacy is dependent on model parameterization, we show that HAS is applicable regardless timescale differences between the network and the spreading dynamics. The algorithm is particularly suitable for processes where the spreading- and contact processes are dependent (adaptive networks). To highlight potential applications, we study the impact of diagnosis- and incidence-driven behavioural changes on a virtual epidemic and examine the impact of adaptivity on the spreading process.

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MS43

Concentration and Mean Field Approximation Results for Markov Processes on Large Networks

We study Markov processes on weighted directed hypergraphs where the state of at most one vertex can change at a time. Our setting is general enough to include simplicial epidemic processes, processes on multilayered networks or even the dynamics of the edges of a graph. Our results are twofold. Firstly, we prove concentration bounds for the number of vertices in a certain state under mild assumptions. Our results imply that even the empirical averages of subpopulations of diverging but possibly sublinear size are well concentrated around their mean. In the case of undirected weighted graphs, we completely characterize when said averages concentrate around their expected value. Secondly, we prove (under assumptions which are tight in some significant cases) upper bounds for the error of the N-Intertwined Mean Field Approximation (NIMFA). In particular, for symmetric unweighted graphs, the error has the same order of magnitude as the reciprocal of the average degree, improving the previously known state of the art bound of the inverse square root of the average degree.

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MS43

How Collective Modes Shape Solitary States in Oscillator Networks

Networks of oscillators exhibit a rich behavior ranging from complete synchronization, over partially synchronized so-called solitary states, cluster synchronization and chimeras, to full disorder. In this talk, we focus on solitary states that occur frequently when a synchronous system of networked oscillators is perturbed locally. Remarkably, several asymptotic states of different frequencies can coexist at the same node. Their understanding is crucial in applications such as power grid stability. Here, we uncover the mechanism underlying this multistability: In addition to a well-understood decoupled state, the resonant back-reaction of the network's collective modes on the solitary can lead to a large energy transfer between them, and the solitary's frequency adaptation can tune the system towards a resonance.

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MS44

Activity Patterns in Ring Networks of QIF Neurons with Synaptic and Gap Junction Coupling

We present a mean field description of a ring network of quadratic integrate-and-fire (QIF) neurons with both synaptic and gap junction coupling. The network shows a variety of states including standing waves, traveling waves and lurching waves. We show a computationally efficient way to study these solutions, using the fact that the dynamics are governed by a Riccati equation. We do this by deriving a self-consistency equation for the current applied to neurons, rather than the dynamic variables of the network. Our results give insight into the effects of gap junctional coupling on the dynamics of such networks.

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MS44

Model-Based Prediction of Behavior from Collective Brain Dynamics

Resting-state brain dynamics measured by the functional magnetic resonance imaging (MRI) can effectively be modeled by whole-brain dynamical models that were originally designed to provide a biophysically-inspired approach to investigate the relationship between brain structure and function as given by the structural and functional brain connectivity, respectively. The modeling outcomes can be employed to investigate a variety of brain properties and phenomena, in particular, the inter-individual variability of brain dynamics and brain-behavior relationship. Here we discuss a workflow on how multi-modal MRI data can be modeled, simulated and then applied to prediction of human behavior and clinical scores by machine learning. We evaluate the performance of such an approach through several examples such as sex classification, differentiation Parkinsonian patients from healthy controls and prediction of cognition or personality traits. We in particular show that incorporating the simulated data into machine learning can significantly improve the prediction performance compared to using empirical features alone. Our results suggest considering the outputs of the dynamical brain models as an additional neuroimaging data modality that can capture brain features that are difficult to measure directly.

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MS44

Second-Order Kuramoto Model of Oscillatory Networks: When High-Order Approximation Matters

Analysis of oscillatory networks and their synchronization is commonly performed using first-order phase approximation. The most illustrative example is the celebrated Kuramoto model and its extensions. In this presentation, starting with a network of non-identical Stuart-Landau oscillators with arbitrary pairwise linear coupling, we derive the phase dynamics equations in the second-order approximation. The main properties of the high-order terms are: (1) in addition to pairwise terms, triplet terms appear, and (2) the term coefficients depend on the frequencies of the interacting units. In particular, we explicitly write the second-order dynamics for the standard chimera setup of non-locally coupled units and the case of globally coupled oscillators. We illustrate the usefulness of the directed model using examples where the first-order Kuramoto model cannot capture the effects. These examples include an explanation of the remote synchronization of indirectly coupled units and a description of a chimera's shape in a ring of non-locally coupled oscillators.

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MS45

A Fast Interactive Tool for Fitting Cardiac Models to Experimental Data

We present CardioFit, a tool to fit cardiac action potential model parameters to cardiac time-series data using particle swarm optimization (PSO). CardioFit can use any combination of voltage, calcium, and action potential duration data, and is able to run quickly due to its highly parallel GPU implementation. We show that the tool is capable of finding good fits to both experimental data and data from models of varying complexity and can even reproduce bifurcations leading to period-2 alternans behavior by fitting to data from several pacing periods. In this presentation, we also show novel features, such as simultaneous fitting of voltage and calcium data; the ability to fit to an arbitrary pacing protocol, which can improve model identifiability; and the availability to fit data to more detailed mechanistic models. Finally, we discuss the use of alternative interaction networks for PSO, which can place a greater emphasis on exploration of the parameter space than the baseline PSO algorithm. The presentation will include methodological and implementation information, a live demonstration of the tool, and walking through several examples of use-cases.

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MS45

Heterogeneous Conduction Due to Multistability and Stochastic Effects in the Dynamics of Gap Junctions

We study the cardiac action potential propagation in a one-dimensional fiber, where cells are electrically coupled through gap junctions (GJs). We consider gap junctional gate dynamics that depend on the intercellular potential. We find that different GJs in the tissue may end up in two different states: a low-conducting or a high-conducting state, resulting in a highly heterogeneous conduction substrate. We first present evidence of the dynamical multistability that occurs by setting specific parameters of the GJ dynamics. Subsequently, we explain how the multistability is a direct consequence of the GJ stability problem by reducing the dynamical systems dimensions. The conductance dispersion usually occurs on a large time scale, i.e., thousands of heartbeats. Finally, we show that multistability is also present in a more detailed, subcellular model, and when considering stochastic dynamics of the gap junctions.

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MS45

The Role of Intercell Ephaptic Coupling in Generating Small-scale Arrhythmogenic Spiral Wave aActivity

Reentrant electrical waves in the heart, known as spiral waves, are thought to underlie a number of abnormal, rapid cardiac rhythm patterns, including tachycardia and fibrillation. In turn, so-called discordant electrical alternans, a period-two pattern of waves that are arranged spatially into regions that are out of phase with one another, is thought to be a precursor for the creation of patterns containing multiple spiral waves. However, standard gap-junction coupling between cardiac cells typically cannot support out-of-phase region sizes small enough to produce spiral waves that can physically fit into human and canine hearts. Previously, we have shown that, when so-called ephaptic coupling is present, discordant alternans can develop with spatial scales that appear to be small enough. In this talk, we investigate whether tissue containing ephaptic intercell connectivity is indeed susceptible to the development of small-scale spiral wave activity. We find, through computer modeling, that the answer is "yes"; however, we also find the that the pattern of both longitudinal and transverse cell-interconnectivity plays an important role.

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MS46

A Computational Model for Cortical Spreading Depression

Cortical spreading depression (CSD) is a wave of neural depolarization which slowly spreads across the cortex. It is accompanied by a disturbance in ion concentrations, followed by a prolonged neural silence which may last for several minutes. Despite its dramatic consequences, CSD has only recently been detected in humans, and it remains difficult to detect it noninvasively. Its increasing clinical importance creates an urgent need for mathematical models that can account for the involved biological mechanisms. So far, modeling CSD dynamics has concentrated on the ignition phase but not on the propagation of CSD. To complement this, we propose a neural population framework which models the CSD dynamics of both ignition and propagation phases. The model is based on an integro-differential system inspired from the Wilson-Cowan-Amari formalism. It is based on an excitatory-inhibitory neural population pair which is coupled to a potassium concentration variable. The model is spatially extended to a cortical layer patch, generalizing the ignition dynamics to the propagation dynamics. The novelty is that the model takes into account the ionic modulation of the neural transfer functions. This allows us to test the hypothesis of that CSD is triggered by very high firing rate of interneurons which is caused by the genetic mutations leading to a gain of function of certain voltage-gated ion channels. The model has been tested on biological experiments and it provides coherent results.

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MS46

Effects of Local Gain Modulation on Probabilistic Selection of Actions

Adaptation of behavior requires the brain to change goals in a changing environment. Synaptic learning has demonstrated its effectiveness in changing the probability of selecting actions based on their outcome. In the extreme case, it is vital not to repeat an action to a given goal that led to harmful punishment. Here, we propose a multiple timescale model where a simple neural mechanism of gain modulation that makes possible immediate changes in the probability of selecting a goal after punishment of variable intensity. Results show how gain modulation determine the type of elementary navigation process within the state space of a network of neuronal populations of excitatory neurons regulated by inhibition. Immediately after punishment, the system can avoid the punished populations by going back or by jumping to unpunished populations. This does not require particular credit assignment at the 'choice' population but only gain modulation of neurons active at the time of punishment. Gain modulation does not require statistical relearning that may lead to further errors, but can encode memories of past experiences without modification of synaptic efficacies. Therefore, gain modulation can complements synaptic plasticity.

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MS46

Observation of Some Neural Fields Models of the Visual Cortex

Developing observation techniques for neural dynamics at the cortical scale presents significant challenges due to the singularly nonlinear and distributed nature of these systems. As a starting point in addressing these complexities, we focus on observer synthesis for three-dimensional neural fields models of the primary visual cortex (V1). These reduced models of cortical activity capture dynamics at the mesoscopic scale, with a focus on how edge-orientation perception drives the diffusion of neural activity. We demonstrate that spatially-averaged measurements can, under certain conditions, provide knowledge equivalent to the full system state. This relies on the models singularly nonlinear structure, driven by a sigmoid function, and requires persistent excitation of the visual cortex. Within this framework, we design a dynamical observer capable of real-time state estimation. For this example, these techniques involve embedding the dynamical system in a higher dimensional space where the smooth dynamics retain only Hlder-regularity but gain a triangular shape that can be exploited for finite time estimation.

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MS46

A Generic Synthesis for Controlling Neural Field Equations

Neural field models are important in theoretical neuroscience to mechanistically interrogate the activity propagation across the cortex. As such, understanding the control properties of these models can provide insights into neural computation and function, potentially informing neurostimulation approaches. The controllability properties of these equations, such as the Wilson-Cowan or Amari-type models, have been investigated for various applications, including feedback stabilization in deep-brain stimulation [Brivadis *et al.*, 2023; Chaillet *et al.*, 2017] and open-loop control of traveling waves [Ziepke *et al.*, 2019]. However, to the authors' knowledge, the general controllability questionthe ability to steer the system between stateswas first addressed by [Tamekue *et al.*, 2024]. This work provided early insights into using time-invariant inputs to steer Amari-type equations over a small time horizon. The proposed input, though informative, was not practical due to its dependence on an abstract operator $O(\tau)$, which is challenging to implement in practice. Moreover, the implicit dependency of $O(\tau)$ on both the state and input complicates the control design even in a short time horizon. Building on these insights, we present a solution expansion for Amari-type equations that enables a more practical feedforward input synthesis for short time horizons. Numerical examples will demonstrate the effectiveness of this approach.

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MS47

A Policy Iteration Method for Inverse Mean Field Games

Mean-field games study the Nash Equilibrium in a non-cooperative game with infinitely many agents, they have a wide range of applications in engineering, economics, and finance. The coupling structure of the forward-backward equations of MFG raises specific difficulties in finding solutions to MFG, and makes it even more challenging to solve its inverse problem. In this talk, I will present a policy iteration method to solve an inverse problem for a mean-field game model, specifically to reconstruct the obstacle function in the game given partial observation data of value functions. The proposed approach decouples this complex inverse problem, which is an optimization problem constrained by a coupled nonlinear forward and backward PDE system in the MFG, into several iterations of solving linear PDEs and linear inverse problems. It substantially simplifies the problems and improves computational efficiency. We will use several numerical examples to demonstrate the accuracy and efficiency of the proposed method, and also discuss its convergence.

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MS47

A Mean-Field Games Laboratory for Generative Modeling

We demonstrate the versatility of mean-field games (MFGs) as a mathematical framework for explaining, enhancing, and designing generative models. We establish connections between MFGs and major classes of flow and diffusion-based generative models by deriving continuous-time normalizing flows and score-based models through different choices of particle dynamics and cost functions. Furthermore, we study the mathematical structure and properties of each generative model by examining their associated MFG's optimality condition, which consist of a set of coupled forward-backward nonlinear partial differential equations. We present this framework as an MFG laboratory which serves as a platform for revealing new avenues of experimentation and invention of generative models. In particular we show how MFG structure can inform new score-based generative models that can be learned faster with less data, and normalizing flows that can robustly learn data distributions supported on low-dimensional manifolds.

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MS47

A Pde-Based Model-Free Algorithm for Continuous-Time Mean-Field Game

This talk extends the PhiBE framework to address continuous-time mean-field games (MFGs) in settings where the underlying dynamics and interactions among agents are unknown. While traditional model-free MFG algorithms are straightforward to implement, they often struggle with accuracy due to discrepancies between the continuous-time dynamics and discrete-time data. In contrast, model-based PDE approaches provide higher accuracy but assume full knowledge of system dynamics, which is often unidentifiable in practice. Our proposed algorithm overcomes this limitation by introducing a new PDE-based Bellman equation that directly leverages discrete-time observations to approximate Nash equilibria without explicit model identification. This method enables reliable optimal value function in continuous-time settings and adapting to scenarios with slowly varying dynamics. The result is a robust and precise solution framework for complex, large-scale MFG problems, bridging the gap between model-free and model-based methodologies.

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MS48

Hamiltonian Dynamics of Three Body Interactions

Pairwise interactions under central forces is a key component of Newtonian dynamics, forming the basis for all of celestial mechanics. What would happen if, instead, interactions only occur between triplets? A triplet of point masses forms a triangle in space, and we assume that the energy has a standard kinetic plus potential form. The potential can depend upon the geometry of the triangle. We were motivated by recent studies of dissipative dynamics on hypergraph networks. In the Hamiltonian context, three body interactions have been studied in atomic physics since 1943 in the work of Axilrod and Teller for the semi-classical van der Waals force. Here the potential depends on the product interparticle distances and on the cosines of the angles. Similar models include interactions of polar molecules in an optical lattice and colloids, where the potential depends only on the interparticle distances. We study triple interactions for which the potential depends only on the area of the triangle, which by Herron's formula is a function of the side lengths. The resulting "areal forces are normal to each side of the triangle. For such a system, the center of mass and total angular momentum are conserved. The simplest case of a single triplet in the plane, which has six degrees of freedom, can be reduced to four in Jacobi coordinates. We show how chaotic dynamics is manifested for several examples, e.g. an inverse area law and an areal-Lennard-Jones potential.

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MS48

Description of Transport Barriers in Nontwist Maps

Nontwist systems violate the twist condition, resulting in a non-monotonic relationship between momentum and velocity in phase space. These systems exhibit characteristic features, such as twin island chains and shearless curves. The universal behavior of nontwist systems can be described by the standard nontwist map (SNM), a two-dimensional map that serves as the simplest model violating the twist condition. In a phase space composed of both regular and irregular orbits, the movement of chaotic trajectories is restricted by transport barriers, which may be total barriers, like the shearless curve, or partial barriers formed by the stable and unstable manifolds of hyperbolic points. Here, we describe an effective barrier that persists even after the shearless torus is broken. Being a degenerate system, the SNM contains twin islands, and consequently, twin hyperbolic points. The crossing between manifolds and the resulting structures depend intrinsically on the period parity of these islands. For odd-periodic twin islands, we identify the well-known manifold structure that can act as a turnstile for chaotic trajectories. In contrast, for even-periodic twin islands, the manifolds of different hyperbolic points form an intricate chain with a dipole-like configuration. We refer to this structure as a torus-free barrier, as it makes the transport of chaotic trajectories through the chain a rare event, and for most predefined iteration times, transport is effectively null.

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MS48

Transport in the Earth-Moon System

Transport in the Earth-Moon system In this talk we address the natural dynamics of a particle in the Earth-Moon system. As a model we use the well-known planar Bicircular problem where the direct gravitational effect of the Sun on the particle is added as a periodic time-dependent effect. By means of a stroboscopic section we reduce the problem to the study of a 4D symplectic map. In the presentation we will consider several situations: the transfer of lunar ejecta to the Earth, the capture of a Near-Earth asteroid in the Earth-Moon system, and the connections between the neighborhood of the points $L_{1,2}$ of the Earth-Sun system and the neighborhood of the L_3 point of the Earth-Moon system. We will see that, in all the cases, the skeleton of this transport consists of the stable/unstable manifolds of suitable invariant tori. The mechanism is very general and it should be found in many physical models.

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MS48

Nonlinear Magnetohydrodynamic Mode Dynamics and the Formation of Non-Integrable Magnetic Fields

Non-axisymmetric, toroidal magnetic fields can admit a variety of structures that are not present in axisymmetric fields. These structures, which include magnetic islands and chaotic magnetic fields, can significantly modify the transport properties of the plasmas in which they are embedded. In magnetically confined fusion plasmas, heat transport is strongly anisotropic. Heat conduction parallel to the magnetic field is stronger than transport in the direction perpendicular to it by at least six orders of magnitude. Consequently, the structure of the magnetic field is a key determinant of the heat transport properties in these plasmas. In this presentation, we discuss nonlinear interactions between macroscopic, magnetohydrodynamic (MHD) instabilities as a mechanism for changing magnetic field structure. This includes disordering of magnetic field lines due to mixing of the plasma fluid that is induced by the growth of MHD instabilities. We discuss the nonlinear characteristics of MHD instabilities, such as saturation amplitude, how they influence these changes and the impact on heat transport.

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MS49

Metastable Hierarchy in Abstract Low-Temperature Lattice Models

The phenomenon of metastability, and especially its hierarchical decomposition, is ubiquitous in a large class of dynamical systems, both real-life and theoretic, with two or more locally stable states. In this talk, I will briefly review this phenomenon in the setting of abstract lattice models at low temperatures. I will also talk about a few examples which include Glauber and Kawasaki dynamics for Ising/Potts models. The talk is partially based on a joint work with Insuk Seo (SNU).

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MS49

Generic Generation of Noise-Driven Chaos in Stochastic Time-Delay Systems

Nonlinear time-delay systems arise in many real-world applications. These systems produce inherently delay-induced periodic oscillations which are, however, too idealistic compared to observations. We exhibit a unified stochastic framework to systematically rectify such oscillations into oscillatory patterns with enriched temporal variabilities through generic, nonlinear responses to stochastic perturbations. Two novel paradigms of noise-driven chaos in high-dimension are identified. They are fundamentally different from chaos triggered by parameter-space noise. Noteworthy, is a low-dimensional stretch-and-fold mechanism, leading to stochastic strange attractors exhibiting horseshoes-like structures mirroring turbulent transport of passive tracers. The other is high-dimensional in nature, with noise acting along the critical eigendirection and transmitted to "deeper" stable modes through nonlinearity, leading to stochastic attractors exhibiting swarm-like behaviors with power-law and scale-break properties. The theory is applied to a cloud-delay model to parameterize the missing physics such as intermittent rain and Lagrangian turbulent effects. The stochastically rectified model reproduces with fidelity complex temporal variabilities of open-cell oscillations exhibited by high-end cloud simulations. This is a joint work with Mickael Chekroun (UCLA, Weizmann Institute), Ilan Koren (Weizmann Institute), and Huan Liu (Weizmann Institute).

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MS49

The Most Probable Transition Pathway of a Predator-Prey System under Noise

Stochastic population dynamics plays a crucial role in biological systems. The number and distribution of biological populations often affect the stability of ecosystems, and even lead to the transition of ecosystems from one steady-state to another. The transition between different states of a population has a significant impact on both population dynamics and biological evolution. we examined a stochastic population model and used Onsager-Machlup action functional and neural shooting method to obtain the most probable transition pathway between different states. Moreover, we analyzed the influence of noise intensity, maximum harvest rate s and time T on most probable transition pathway in two different parameter scenarios. Our research may provide a better understanding of evolutionary process such as genetic variation in populations and the evolution of species adaptation, meanwhile, may provide a theoretical guidance for species conservation and management in real world.

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MS50

Estimating Dynamics and Data Assimilation to Detect Obstructive Sleep Apnea

Revisiting the challenge of using ECGs to detect obstructive sleep apnea which was posed by the Computers in Cardiology Meeting in 2000, I model dynamics at two levels. First I fit the PQRST sequences in the ECG of each patient with a model that has rigid timing and use the delay between T waves and subsequent P waves to estimate heart rate. The analysis relies on the idea that once a P wave is launched in the SA node, the rest of the pattern follows from wave propagation through the roughly fixed physiology of the patient's heart. The model ignores the mechanisms of wave propagation in the heart and how that produces the ECG signal. The second model, of heart beat timing, accounts both for how CO2 levels varying over time scales of tens of seconds affects heart rate and for how inhalation and exhalation advance and retard heart beat timing respectively. The model ignores details of the PQRST pattern and any physiology. At the 2001 Snowbird meeting I presented an algorithm and nice results addressing the challenge based on the idea of finding a maximum probability sequence of classifications. In any remaining time, I will talk about the exponential complexity of finding maximum probability sequences of classifications and how luck gave me nice results in 2001.

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MS50

Chemical Reaction Networks from the Molecular Description to the Continuum

The continuum description of chemical reaction networks works in terms of chemical concentrations which are represented as real numbers and the equilibrium concentrations are found by solving coupled nonlinear equations. The molecular description treats chemical species as discrete entities which are typically modeled via the chemical master equation. At equilibrium particles still react and obey an equilibrium distribution which is the standard Boltzmann distribution. I will discuss the relationship between these two view points and will show how to obtain the equilibrium solution for the continuum description from the Boltzmann distribution for the discrete molecular description. While these results are not surprising it might be satisfying to see how the two points of view carry over into one another in the limit of large particle numbers.

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MS50

Modeling Spatial Infectious Disease Dynamics: Why Ancestral Genomic Admixture Is Important

We know that the genes that a pathogen carries, and their variations, are critical in understanding its pathogenicity. Each named COVID-19 variant carried unique virulence. In addition, it is becoming increasingly apparent that infections require an interplay between a pathogen and the human hosts background genomics. In the infant, before exposure to pathogens and the creation of immune memory and antibodies, the only defense is what they were born with – the innate immune system. Such innate systems reflect a persons genomic ancestry. For rural peoples in the developing world, modern migration patterns tend to be from rural to cities. So one might anticipate that rural peoples may retain to this day their ancestral migration patterns, reflected in ancestral genome admixtures. If so, this suggests that such widely varying genomic backgrounds would lead to substantial differences in the risk of and outcomes from serious infections. In this talk, I will present new data from whole genome sequencing from over 1000 African infants, demonstrating that such genomic backgrounds can be identified and correlated with the risk of disease.

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MS51

Causal Relationships among Evacuating Dyads Under Stress

Real emergency evacuations almost always occur under duress. However, most laboratory experiments on evacuations are naturally performed in a safe environment to avoid injuries and emotional trauma. This makes it difficult to inform or validate attempts at designing realistic models of pedestrian evacuation. We describe recent experiments that involved subjecting a subset of the evacuating group of participants to a cold pressor task or CPT—a reliable inducer of physiological stress that entails submerging their hand in ice water for up to two minutes—before they exit a maze under low light conditions and safety alarms. Multi-dimensional time series data consisting of each participants movement (head position and orientation), posture (shoulder positions), and physiology (heart rate variability and cardiac impedance) was tracked in real time as they evacuated the maze. This talk will focus on causal analysis on a subset of this data to determine how information is transmitted among dyads: two participants evacuating the maze when at most one of them has been subject to CPT. We calculate transfer entropy between pairs of one-dimensional time series of speed, turn rate, and heart rate variability across participants to identify the underlying directed network structure corresponding to information transmission through movement and physiology. This analysis is expected to form the first step towards a data-driven model of high-stress pedestrian evacuations.

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MS51

Diverse Populace of Virtual Worlds with Generative Models

Over the past two decades the field of pedestrian simulation has experienced a dramatic increase in the number of tools, approaches, and algorithms focusing on creating compelling motions of human crowds. Despite recent advancements, though, simulated humans lack the versatility of their real counterparts and mostly focus on avoiding collisions with each other and the environment. In this talk, I will highlight our recent efforts on advancing the behavioral capabilities of 3D humanoids by taking advantage of recent advancements in deep generative models and reinforcement learning while leveraging publicly available crowd datasets. I will conclude the talk with discussing how we can simulate diverse crowd behaviors via foundational models while moving away from the need of having access to expert reference data.

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MS51

Fast Estimation of Delay Margin in a Connected Vehicle Network

Traffic congestion is a major issue worldwide as it is associated with deaths, traffic jams, emissions, and economic losses. Research into traffic flow dynamics has been a focus in engineering and physics since the 1950s. Mathematical models have been formulated to understand how vehicles interact with each other, allowing for the identification of factors leading to congestion. Microscopic models, in particular, shed light on how individual vehicles affect overall traffic flow, enabling the identification of conditions that trigger traffic instabilities. The introduction of connected vehicle networks has amplified the need to understand the effects of time delaysranging from human reaction times to sensor and communication lagsas these delays risk stability. Given that traffic will likely remain a mix of automated and legacy vehicles, analyzing how delays can affect the stability of these heterogeneous network dynamics is crucial. Delay Margin (DM) is the largest delay the dynamics can withstand without losing stability. It can be utilized as a metric to investigate the effects of vehicle connectivity on stability. In this study, connectivity is quantified by betweenness centrality (BC), and the relationship between BC and DM is investigated summarizing from our recent results (Wang, Sipahi 2024 Physica A). Understanding this relationship can provide insights for optimizing traffic networks without directly computing DM, which is otherwise computationally expensive.

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MS52

Multi-Pulse Pinning in Spatially Periodic Systems Arising in Nonlinear Optics

We present an abstract framework to establish the existence and spectral (in)stability of multiple pulse solutions pinned to periodic potentials in semilinear evolution problems. We adopt a spatial dynamics approach to construct these solutions near formal superpositions of well-separated primary pulses by characterizing invertibility through exponential dichotomies. With the aid of Evans functions we prove that the spectrum of the system's linearization about such a solution converges to the union of the spectra of the primary pulses as the distances between them tend to infinity. We apply our method to the Lugiato-Lefever equation with periodic potential, yielding the existence and spectral (in)stability of multi-soliton solutions near formal superpositions of bright NLS solitons. This is joint work with Bjrn de Rijk.

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MS52

Analysis and Simulation of Localized Structures in Biological Models Involving Nonlocal Interactions

Many biological systems include transport or diffusion processes which are nonlocal. Examples include neural field models, which use nonlinear convolution operators to describe short- and long-range connections between cells, and ecological models, where the spread of individuals or plant seeds is assumed to follow a nonlocal or anomalous form of diffusion. These systems are often described using integro-differential equations, which can be challenging to analyze and simulate. In particular, when the convolution operator describing nonlocal interactions is not well approximated by the Laplacian, it is not possible to reduce the model to a set of partial differential equation. This talk summarizes some of the analytical and computational tools that can be used to study coherent structures in these systems. We present examples that illustrate the effect that nonlocal spread can have on these solutions, placing particular emphasis on localized structures that form in a vegetation model.

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MS52

Interface Motion in Multi-Component FitzHugh-Nagumo-Type Systems

It is well known that front interfaces in bistable isotropic reaction-diffusion equations are asymptotically stationary or move with constant speed. This does not in this generality for systems with multiple components. In particular, it is known that self-organised front motion through interacting components occurs in system with one fast component governed by an Allen-Cahn equation that is coupled to one or two slow linear equations. Here we consider N such slow components and study existence, stability and bifurcations of stationary and uniformly travelling front solutions near the singular limit. Combining an Evans function and a functional analytic approach we find that the dynamics of front speeds obeys an N-th order ODE. Analysing the normal form, for $N = 3$ we prove that chaotic dynamics occurs in the sense of an unfolded Shil'nikov homoclinic orbit. Numerical study guided by our analytic findings complement these results. This is joint work with Martina Chirilus-

Bruckner (Leiden) and Peter van Heijster (Wageningen).

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MS52

Oscillatory Moving Spiky Patterns in Some Three-component Reaction-diffusion Systems

Spatial localized patterns have been observed in diverse physical and chemical experiments. The modeling of these experiments often generates nonlinear reaction-diffusion (RD) systems that admit spatial inhomogeneous solutions localized in small regions. As prototyping models to produce well-localized solutions, several well-known two-component RD systems, such as the GiererMeinhardt model, the GrayScott model and the Schnakenberg model have been extensively studied. In this talk, I will review some studys on two-component reaction-diffusion system and discuss new phenomenon in corresponding three-component systems.

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MS53

Linear Response and Control of the Statistical Properties of Dynamics

The concept of linear response of a dynamical system describes how the statistical properties of the system change when a certain ”infinitesimal” perturbation is applied to the system. This concept has important relations with the study of climate models and climate change. One inverse problem associated with linear response is the optimal response, which finds the best infinitesimal perturbation in order to modify the statistical properties of the system in some wanted direction. One way to formalize the problem is by considering a given observable and searching for the optimal perturbation in order to maximize the average of the observable. The existence of an optimal solution has been proved in some classes of deterministic and random systems and numerical methods for its approximation have been shown. In the talk, we briefly discuss the mathematical structure of the problem and review some recent results on the control of the statistical properties of random dynamical systems and expanding maps. Moreover, we explain how to use the fast adjoint response method for the optimal response of hyperbolic deterministic systems. The fast response method combines the adjoint shadowing formula (a path-perturbation method), and the equivariant divergence formula. It is used both in the estimation of the linear response operator and the numerical computation of the optimal response. We also show how to solve the optimal response problem for SDEs.

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MS53

Differentiating Unstable Diffusions

The linear response is the parameter derivative of averaged observables of a (random) dynamical system. We start by reviewing three basic methods. The path-perturbation formula does not work for chaos; the divergence formula is cursed by dimensionality; the kernel-differentiation formula is expensive for small noise. These basic methods should be combined for the fastest and most accurate approximation of real-life applications. Moreover, we derive the path-kernel formula for the linear response of SDEs. Here the parameter controls initial conditions, drift coefficients, and diffusion coefficients. Our formula tempers the unstableness by gradually moving the path-perturbation to hit the probability kernel. It does not assume hyperbolicity but requires noise. It extends the path-perturbation formula, the Bismut-Elworthy-Li formula, and a formula in Malliavin calculus. Then we derive a pathwise sampling algorithm and demonstrate it on the 40-dimensional Lorenz 96 system with noise.

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MS53

Measure-Theoretic Koopman Operator

The Stochastic Koopman (SKO) operator has been associated in literature with dynamical systems that exhibit stochastic behaviour. However, the SKO can only recover the expectation of an observable along the trajectory and requires tracking data for its computation. In this work, the Distributional Koopman Operator (DKO) is introduced as a novel framework for analyzing stochastic dynamical systems where only aggregate distribution data is available, avoiding the need for particle tracking. Our DKO framework extends the Koopman operator to act on observables of probability distributions, leveraging the transfer operator to propagate these distributions forward in time. We analyse the proprieties of this new operator, and show how one can recover information about higher order moments from this formulation. Lastly, we design an algorithm to compute the DKO from data.

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MS53

Entropic Transfer Operators for Stochastic Systems

Transfer operators provide a statistical description of dynamical systems from which low-dimensional effective coordinates and macroscopic features such as metastable states, coherent sets, and cycles can be extracted. An important task is the estimation of the transfer operator from observed transition data. To make this problem well-posed, some form of compactifying approximation must be applied, for instance via a stochastic blur of the original system. Entropic optimal transport induces a blur operator which preserves the original invariant measure, and which can be applied to discrete point data in a natural and asymptotically consistent way. Its suitability for estimating the transfer operator of deterministic systems has been demonstrated recently [Junge et al., Entropic transfer operators, Nonlinearity, 2024]. In this presentation we further extend this approach to stochastic systems, a quantitative convergence analysis, and an out-of-sample extension method for new data points.

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MS54

Arnold Diffusion in the Full Three-Body Problem

An arbitrarily small perturbation of an integrable Hamiltonian system can lead to macroscopic changes of its constant of motion. Such behaviour is referred to as Arnold diffusion. We will present a geometric mechanism which leads to such phenomenon. As an application of our method we will consider the Neptune-Triton-asteroid system, with the mass of the asteroid playing the role of the perturbation parameter. The proof is computer assisted.

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MS54

Validated Numerical Computations of Convolutions in the Borel Plane

The Borel transform can be used to study functional equations whose solutions are C infinity but not analytic. Such equations describe invariant manifolds attached to parabolic fixed points and the solution of heat type equations. A fundamental challenge in working with the Borel transform is that it turns products into complex convolutions. This work aims to develop validated numerical methods for complex convolutions which can then be used in computer assisted proofs involving the Borel transform.

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MS54

Computing Manifolds for Billiard Maps on Perturbed Elliptical Tables

Dynamical billiards consist of a particle on a two-dimensional table, bouncing elastically each time it hits the boundary. The successive bounce location plus bounce angle forms a two-dimensional iterated map, which was first studied by Birkhoff. On elliptical tables, the dynamics of billiard maps are completely integrable. The Birkhoff conjecture proposes that this is the only smooth convex table for which this is true. In this spirit, we present an implicit real analytic method for billiard maps on perturbed elliptical tables. This method allows us to compute stable and unstable manifolds using the parametrization method. While the results as yet are numerical only, our method is devised so it can in future be validated. This is joint work with Patrick Bishop, George Mason University and Jay Mireles James, Florida Atlantic University.

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MS54

An Improvement of Rigorous Integrator for Semilinear Parabolic PDEs via Evolution Operator Approach

In recent works of computer-assisted proofs, we have developed an approach of rigorous forward integration in time for semilinear parabolic partial differential equations (PDEs) via semigroup theory. This approach formulates a zero-finding problem on the Banach space of space-time variables to find a solution of time-evolutionary PDEs. By finding a fixed-point of the Newton-like operator for this zero-finding map, we can prove the existence and local uniqueness of the solution in the neighborhood of an approximate solution with computer-assistance. We note that the Fréchet derivative of the zero-finding map at the approximate solution is characterized by the linearized operator, and the uniqueness of the solution to the linearized problem allows the explicit formulation of the inverse operator of the Fréchet derivative. In this talk, we show an improvement of this methodology by using multi-step approach, evaluating the evolution operator over multiple time steps. This improvement allows us to succeed more long time integration and to apply the integrator for the time boundary value problems of semilinear parabolic PDEs, providing a framework for further applications.

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MS55

Whitham Modulation Theory for Davey-Stewartson System

Whitham modulation theory is developed the Davey-Stewartson system, a nonlocal extension of the nonlinear

Schroedinger equation in 2+1 dimensions. A system of quasilinear first-order PDEs is obtained through a multiple scales expansion and averaging over one oscillation period of the periodic traveling wave solutions. Subsequently, the system is transformed into a hydrodynamic Whitham system, which is then utilized to investigate the transverse stability of periodic traveling wave solutions. The obtained results demonstrate excellent agreement with numerical simulations.

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MS55

Progress on the Stability of Periodic Internal Waves

Internal waves develop at the interface between two fluids of different densities. If both fluids are assumed to be irrotational and incompressible, one can derive governing equations for the interface similar to the Euler equations for free surface gravity waves. In this presentation, we prove the existence of small-amplitude, periodic internal waves and investigate their spectral instabilities using asymptotic methods and rigorous analysis for the first time.

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MS55

Experiments on Nonlinear Water Waves in Shallow and Deep Water

Title: Talk Title: Experiments on Nonlinear Water Waves in shallow and deep water Abstract: We present experiments on two types of waves. The first are those evolving from an initial disturbance of a water surface on water that is shallow, intermediate-depth, or deep. The initial disturbance is either positive or negative. We compare measurements with predictions from temporal and spatial versions of the KdV equation and the Whitham equation, with and without dissipation and show that the spatial Whitham equation with dissipation predicts well the measurements in all depths, even in deep water. This work [1] is in collaboration with J Carter and P Panayotaros. The second are periodic waves perturbed with a subharmonic frequency. These experiments are motivated by stability results for extremes amplitude Stokes waves by [2]. [1] Carter, J. D., Henderson, D., Panayotaros, P. (2024) The Spatial Whitham Equation. Journal of Fluid Mechanics. Accepted. https://doi.org/10.48550/arXiv.2402.14643 [2] B. Deconinck, S. A. Dyachenko, P. M. Lushnikov, and A. Semenova, The instability of near-extreme Stokes waves, Proceedings of the National Academy of Sciences (2023), 120(32), p.e2308935120, https://doi.org/10.1073/pnas.2308935120

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MS55

Stokes Waves and Their New Secondary Bifurcations

The study of surface gravity waves is crucial for understanding the formation of rogue waves and whitecaps in ocean swell. Waves originating from the epicenter of a storm can often be approximated as unidirectional. In this presentation, we will explore periodic traveling waves on the free surface of an ideal, infinitely deep, two-dimensional fluid. We will focus on surface waves of permanent shape, and present new families of Stokes waves with two crests per wavelength.

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MS56

Topological Feature Selection for Time Series Data

I will describe how tools from applied topology, e.g. persistent homology, may be used to identify components of time series most responsible for observed cyclic dynamics. In this setting, I will show that derivatives of the persistent homology may be computed explicitly and describe a simple algorithm for gradient descent. As an example, we will consider neuronal data from the model organism C. elegans and identify subsets of neurons driving global brain dynamics in the spirit of dimensionality reduction.

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MS56

Unraveling Aster and Ring Structures in Cellular Actin Filaments Using Topological Data Analysis

Actomyosin is a dynamic network of interacting proteins that reshapes and organizes in a variety of structures that are essential in cell movement, cell division, as well as physiological processes such as wound healing. Agent-based models can simulate realistic interactions between actin filaments and myosin motor proteins inside cells. These stochastic simulations reproduce bundles, clusters, and contractile rings that resemble biological observations. We have developed techniques based on topological data analysis to understand spatio-temporal data extracted from these protein network interactions. Recently, we have been interested in adapting the framework of vines and vineyards in order to track topological and geometrical features through time-parameterized stacks of persistence diagrams. This approach allows us to quantify characteristics of formation and maintenance of relevant actin structures such as rings and asters in simulated datasets. This is joint work with Niny Arcila-Maya.

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MS56

Personalizing Computational Models to Construct Medical Digital Twins

To realize the promise of personalized medicine, we need to be able to integrate different types of data collected from a given patient into a computational framework that enables decision making about optimal interventions to help this patient to either maintain or regain health. Digital twins represent such a framework, once the technology is sufficiently developed. A fundamental problem that currently does not have a widely applicable solution is how to calibrate a generic computational model of human biology to a given patient at a given time. In this talk, we present a solution to this problem for the agent-based model framework, commonly used to capture stochastic and spatially heterogeneous biological processes, such as tumor growth or immune system dynamics.

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MS56

Topological Data Analysis of Skin Patterns on Zebrafish

Zebrafish are known for their pigment patterns which arise from the interactions between different types of pigment cells. We show interest in developing a mathematical framework, using topological data analysis, to quantify certain properties of such skin patterns. Using a sweeping filtration approach, we categorize these patterns based on their topological persistence, identifying robust features such as the counts and widths of stripes, breaks, and bridges. This allows us to identify abnormalities in skin pattern development, which may indicate health or genetic issues in the fish, offering potential applications in biological research, genetics, and developmental biology.

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MS57

A Novel Image-Based Neuronal Network Model Framework for Understanding Visual Multistability and Neurological Disorders

While perceptual multistability arises from many types of stimuli across different sensory systems, there are common dynamical features that may be rooted in universal organizing principles underlying perception. We probe the mechanisms responsible for visual multistability using a neuronal network model framework in which a set of realistic images directly drives competing pools of neurons with nonlinear dynamics. Incorporating balanced network architecture, long-range connections from excitatory neurons in one pool to inhibitory neurons in the other pools, and a dynamic spiking threshold, the model produces irregular percept switching and replicates key experimental observations. Using a sequence of short-time observations of neuronal dynamics, we derive a methodology for reconstructing the dynamic percept that generalizes to an arbitrary number of percepts. The model dynamics illustrate that perceptual alternations are potentially rooted in the breakdown of balance between excitation and inhibition, with more balanced dynamics generally facilitating longer dominance durations. Finally, we show increasing the ratio of excitatory to inhibitory inputs in the network, either by increasing excitatory connection strengths or decreasing inhibitory connection strengths, systematically yields longer dominance durations as observed for individuals with autism, and we thus demonstrate support for the excitation/inhibition imbalance hypothesis for autism.

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MS57

Fluid Dynamics in Retronasal Olfaction

Previous studies have demonstrated that orthonasal (nasally inhaled) and retronasal (exhaled) olfaction involve distinctly different brain activation, even for identical odors. Multiple experiments have shown that the difference arises as early as inputs to the olfactory bulb (OB). Why would the bulb receive different input based on the direction of the air flow? We hypothesize that this difference originates from fluid mechanical forces at the periphery: olfactory receptor neurons respond to mechanical, as well as chemical stimuli. Using high-resolution computational fluid dynamics, we are constructing a phase map of the mechanical forces impacting the nasal epithelium over a breath cycle, analogous to the chemotropic map for odorants.

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MS57

Neuronal Network Computation in the Developing Visual Cortex

Spontaneous waves are ubiquitous across many brain regions during early development. Activity from waves occurring in the retina are propagated to downstream areas and are hypothesized to drive the development of receptive fields (RFs). However, the mechanisms underlying the influence of each retinal wave on RF refinement are not well understood. In this work, we build a biologically-constrained mathematical model of the development of the feed-forward RF of neurons in the primary visual cortex. Using this model, we propose a possible mechanism that underlies a pruning process leading to different RF spatial structures. In particular, we quantify how key characteristics of the retinal wave, such as wave speed, width and presentation angle, affect the simulated pruning result and shape of the receptive field. We further elucidate potential mechanisms of learning through analysis of a reduced rate model. In particular, we find mechanisms for the formation of a periodic RF, which may help to understand related periodic RF development in other brain areas such as grid cells under spontaneous waves in the entorhinal cortex.

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MS57

Extreme First Passage Times for Populations of Identical Rare Events

A collection of identical and independent rare event first passage times is considered. The problem of finding the fastest out of N such events to occur is called an extreme first passage time. The rare event times are singular and limit to infinity as a positive parameter scaling the noise magnitude is reduced to zero. In contrast, previous work has shown that the mean of the fastest event time goes to zero in the limit of an infinite number of walkers. The combined limit is studied. In particular, the mean time and the most likely path taken by the fastest random walker are investigated. Using techniques from large deviation theory, it is shown that there is a distinguished limit where the mean time for the fastest walker can take any positive value, depending on a single proportionality constant. Furthermore, it is shown that the mean time and most likely path can be approximated using the solution to a variational problem related to the single-walker rare event.

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MS58

Mapping Long and Short Timescales of Sleep-Wake Dynamics

The rhythmic processes modulating sleep-wake patterns span multiple timescales, from the 24-h circadian rhythm to daily sleep drive homeostasis to hourly rhythms of rapid eye movement (REM) and non-REM (NREM) sleep stage alternation. These timescales also change across development as sleep patterns consolidate from the polyphasic sleep of infants to the single nighttime sleep episode typical in adults. Using a physiologically based mathematical model for the neural regulation of wake, NREM and REM states, we investigate how NREMREM alternation affects transitions in sleep patterns across development. To understand model dynamics, we numerically construct circle maps that track the evolution of sleep onsets across different circadian phases. The maps are non-monotonic and discontinuous, being composed of branches that correspond to sleepwake cycles containing distinct numbers of REM bouts. As the accumulation and decay rates of the homeostatic sleep drive are varied, we identify bifurcations in the maps that display a disrupted period-adding-like pattern of sleep-wake solutions in the transition between biphasic and monophasic sleep. These bifurcations include border collision and saddlenode bifurcations that initiate new sleep patterns, period-doubling bifurcations leading to higher-order patterns of NREMREM alternation, and intervals of bistability of sleep patterns with different NREMREM alternations.

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MS58

Phase Transformation and Synchrony for a Network of Coupled Izhikevich Neurons

A number of recent articles have employed the Lorentz ansatz to reduce a network of Izhikevich neurons to a tractable mean-field description. In this work, we construct an equivalent phase model for the Izhikevich model and apply the Ott-Antonsen ansatz, to derive the mean field dynamics in terms of the Kuramoto order parameter. In addition, we show that by defining an appropriate order parameter in the voltage-firing rate framework, the conformal mapping of Montbri et al. (2015), which relates the two mean-field descriptions, remains valid. We challenge the assumption that high firing rates indicate high synchrony and show instead that high amplitude oscillations in the firing rate are a signature of highly synchronised neural activity and suggest that EEG and MEG spectral power could be used to infer the synchrony level of underlying neural populations.

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MS58

Observing Hidden Neuronal States in Experiments

In this talk, I will present recent work in which we have constructed systematically experimental steady-state bifurcation diagrams for neurons. A slowly ramped voltage-clamp electrophysiology protocol serves as closed-loop feedback controlled experiment for the subsequent current-clamp open-loop protocol on the same cell. In this way, the voltage-clamped experiment determines dynamically stable and unstable (hidden) steady states of the current-clamp experiment. The transitions between observable steady states and observable spiking states in the current-clamp experiment reveal stability and bifurcations of the steady states, completing an e-approximation of the steady-state bifurcation diagram (e being the speed of the ramp). Furthermore, combining the output of the current-clamp protocole together with that of the voltage-clamp protocol gives an experimental verification of the slow-fast dissection method by J. Rinzel. I will explain how to understand why this is possible, using elements of slow-fast dynamical systems theory. I will comment on the applicability of this approach, as well as, its limitations.

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MS58

Mixed-Mode Oscillations and Phase-Locking in Three Timescale Neuronal Oscillators

Mixed-mode oscillations (MMOs) are complex oscillatory behaviors of multiple-timescale dynamical systems in which there is an alternation of large-amplitude and small-amplitude oscillations. In two-timescale systems, MMOs can arise either from a Canard mechanism associated with folded node singularities or a delayed Andronov-Hopf bifurcation (DHB) of the fast subsystem. While MMOs in two-timescale systems have been extensively studied, less is known regarding MMOs emerging in three-timescale systems. In this work, we examine the mechanisms of MMOs in three-timescale neural oscillators and explore how the interplay between Canard and DHB mechanisms can produce more robust MMOs. Furthermore, we examine the roles of these dynamics in facilitating flexible phase-locking in response to strong periodic inputs in neural oscillators.

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MS59

Confabulation Dynamics in a Reservoir Computer

Artificial Intelligence (AI) has made significant advances in recent years, particularly with the advent of systems like ChatGPT, which is powered by a modern form of Artificial Neural Network (ANN). However, a critical challenge remains, we still understand relatively little about how these systems learn, fail to learn, and generate false information, a phenomenon known as 'confabulation'; when an individual generates a false memory without the intent to deceive (typically associated with Alzheimer's disease and dementia). To address this issue, we study the confabulation dynamics of ANNs in the form of reservoir computers (RCs), which, unlike models such as ChatGPT, are publicly available, mathematically well-defined dynamical systems, and relatively inexpensive to analyse. What further motivates the use of RCs is that they confabulate in their own way; when RCs are trained to reconstruct the dynamics of a given attractor, they can sometimes construct an attractor that they were not trained to construct, a so-called 'untrained attractor' (UA). In this talk, we explore the reasons why UAs exist, the link between UAs and failed reconstruction dynamics, and the influence of UAs when training RCs to reconstruct the bifurcation structure of dynamical systems. These insights not only enhance the explainability, trustworthiness, and safety of AI systems, but may also contribute to improving the understanding of neurological conditions associated with confabulation.

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MS59

Associative Memory and Basin Structure in Multi-State Reservoir Computing

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.

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MS59

Statistics and Dynamics of Attractor Embeddings in Reservoir Computing

A central question in the operation of reservoir computers is, why a reservoir computer (RC), driven by only one time series from a driving system of many time-dependent components, can be trained to recreate all dynamical time series signals of the drive. This leads to the idea that the RC must be internally recreating all the drive dynamics or attractor that is, the RC is creating an embedding (in the mathematical sense) of the drive attractor in the RC dynamics. We show several ways to analyze the RC behavior to help understand what underlying processes are in place, especially regarding if there are good embeddings of the drive system in the RC. We show that statistics we developed can help test for homeomorphisms and diffeomorphisms between a drive system and the RC by using the time series from both systems. These statistics are called, respectively, the continuity statistic and the differentiability statistic and they are modeled on the mathematical definition of a continuous and/or differentiable 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.

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MS60

Sparse Chaos in Cortical Circuits

Nerve impulses, the currency of information flow in the brain, are generated by an instability of the neuronal membrane potential dynamics. Neuronal circuits exhibit collective chaos that appears essential for learning, memory, sensory processing, and motor control. However, the factors controlling the nature and intensity of collective chaos in neuronal circuits are not well understood. Here we use computational ergodic theory to demonstrate that basic features of nerve impulse generation profoundly affect collective chaos in neuronal circuits. Numerically exact calculations of Lyapunov-spectra, Kolmogorov-Sinai-entropy, and upper and lower bounds on attractor dimension show that changes in nerve impulse generation in individual neurons moderately impact information encoding rates but qualitatively transform phase space structure, drastically reducing the number of unstable manifolds, Kolgomorov-Sinai-entropy, and attractor dimension. Beyond a critical point, characterized by a localization transition of the leading covariant Lyapunov vector and the breakdown of the diffusion approximation, networks exhibit sparse chaos: prolonged periods of near stable dynamics interrupted by short bursts of intense chaos. Our results reveal a close link between fundamental aspects of single-neuron biophysics and the collective dynamics of cortical circuits, suggesting that nerve impulse generation mechanisms are adapted to enhance circuit controllability and information flow.

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MS60

Full Lyapunov Exponents Spectrum with Deep Learning from Just One Variable Time Series

The classical technique used to study the behavior of a dynamical system is Lyapunov exponents. Standard algorithms that approximate the full spectrum of Lyapunov exponents use all variables of the system. Deep learning has recently been shown to be useful for the analysis of chaoticity of dynamical systems. As a further step, in this presentation we propose to use deep learning to obtain an approximation of the full spectrum of Lyapunov exponents of a dynamical system using only short time series of a single variable, a situation where classical algorithms can only provide the maximum Lyapunov exponent. Our new strategy is successful and allows us to speed up the full analysis of a dynamical system using only partial data. This is a joint work with Roberto Barrio, Ana Mayora-Cebollero and Carmen Mayora-Cebollero.

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MS60

Node Pruning of Overembedded Reservoir Computers for Attractor Reconstruction

Attractor reconstruction is a method for constructing a geometrically equivalent of the original attractor through a mapping from the observed time series to a high-dimensional space. While traditional approaches to attractor reconstruction have relied on methods such as delay coordinate embedding, more recent attention has focused on Reservoir Computing (RC). An advantage of using RC for attractor reconstruction is that the RC framework can be directly applied to time-series prediction. However, RC approach sometimes faces the challenge that increasing the dimensionality of the reservoir space does not necessarily improve prediction accuracy. This issue is similar to *overembedding* in delay coordinate embedding, where failures in attractor reconstruction and prediction occur due to redundant degrees of freedom in the reconstruction space. In delay coordinate embedding, some approaches have addressed overembedding using continuity statistics to quantify the redundancy of the coordinate of the reconstruction space [L. M. Pecora et al., A unified approach to attractor reconstruction, Chaos (2007)]. In this study, we propose a method to prune redundant reservoir nodes for address overembedding, utilizing continuity statistics. Numerical experiments show that the proposed method effectively prunes reservoir nodes while preserving the properties of the original attractor.

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MS60

Learning Slow Dynamics in Complex Dynamical Systems

Mathematical models for dynamical systems are typically built from first principles. However, capturing the complexity of biological, ecological, and social systems remains challenging, especially when aiming for models that are both efficient and interpretable. To tackle this, various strategies have been developed to build reduced-order models (ROMs) for the examination and analysis of complex multiscale systems. The multiscale nature of these systems often means that their effective or slow dynamics generally unfold within low-dimensional spaces known as slow invariant manifolds (SIMs). Traditionally, SIM approximations are obtained using methods from Geometric Singular Perturbation Theory (GSPT), a framework originally designed to handle dynamical systems with explicit timescale separation. Here, we will demonstrate how combining numerical, machine learning and manifold learning techniques can aid in the bifurcation analysis and control of large-scale, complex dynamical systems. Using Diffusion Maps as a manifold learning technique, we will derive the system variables in a data-driven way. We will discuss two main approaches: (1) the "Equation-Free" approach, which eliminates the need for ROM construction,and (2) a physics-informed machine learning (PIML) approach, based on GSPT,for deriving SIMs in singularly perturbed systems. Both methods leverage the concept that the slow dynamics of large complex systems can be embedded within a low-dimensional manifold.

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MS61

A Methodological Workflow for Epidemic Forecasting

I discuss a systematic workflow for epidemic forecasting, crucial for improving the accuracy and reliability of infectious disease models. We propose a structured validation process, using ordinary differential equation (ODE)-based models, to guide each stage of forecastingmodel calibration, structural and practical identifiability assessments, and robust uncertainty propagation. Through examples using COVID-19 data, we illustrate how integrating simulated and real epidemiological data enhances forecast precision and reliability. Our approach underscores the value of iterative model refinement and targeted validation steps, aiming to optimize data-driven epidemic forecasts for effective public health response.

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MS61

Household-Based Models for Transmission of Dengue Virus

Dengue virus is the most significant viral mosquito-borne infection in terms of its human impact. When considering the spread of dengue at the level of a city, previous work has shown the household to be a key spatial scale on which transmission occurs. In this talk we discuss the formulation and use of household-level models to describe the spread of mosquito-borne diseases. Such models have a long history of use for directly-transmitted infections such as influenza, COVID or the common cold. We will outline the use of branching process theory to analyze household models and discuss threshold parameters akin to the basic reproduction number, R_0. Numerical results will be presented that explore the impact of within and between household transmission and explore different control measures that target these aspects of transmission.

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MS61

Impact of Incidence Functions on Epidemiological Model Dynamics: Mass Action vs. Standard Incidence

The selection of incidence functions in epidemiological models plays a critical role in shaping the disease dynamics, particularly in populations of varying sizes. In this presentation, we examine a model that incorporates post-infection mortality and partial immunity, comparing the effects of mass-action and standard incidence functions. With the mass-action incidence, the model exhibits periodic solutions under certain parameter conditions. In contrast, applying the standard incidence reduces the likelihood of periodic solutions, potentially eliminating them entirely.

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MS61

Modeling for Emergency Management Preparedness of Foreign Animal Diseases in Wildlife: the Case of African Swine Fever in Wild Pigs

Scenario models based on context-specific biology are useful for evaluating impacts of foreign animal disease (FAD) introductions. Such preparedness modeling is applied commonly to FAD preparedness and response in livestock in the United States of America (USA) but less development has been made for important diseases of livestock that could spillover and become endemic in wild animals. African swine fever is an example of a disease that can have devastating impacts on global trade and food security and become endemic in wild pig populations, which challenges elimination. Here we describe the development of preparedness models (using spatial epidemiological simulation), including current status, challenges, and future directions, for informing USA playbooks for implementing a response to African swine fever in wild pigs. We demonstrate the importance of data-driven modeling (i.e., including field-collected data and its processing for integration in the epidemiological models). We quantify effects of host-specific ecological and management factors for identifying effective control strategies that meet policy-maker control objectives and show how a co-development process with emergency management experts can deliver practical results for policy makers.

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MS62

New Geometric Structures for Thermodynamics

In this lecture, we show how almost cosymplectic structures are a natural framework to study thermodynamical systems. Indeed, we are able to obtain the same evolution equations obtained previously by Gay-Balmaz and Yoshimura using Calculus of Variations. The proposed geometric description allows us to apply geometrical tools to discuss reduction by symmetries, the Hamilton-Jacobi equation or discretization of these systems.

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MS62

On Stochastic Integrability of Jacobi

Jacobi's foundational work on Hamilton-Jacobi (HJ) theory provides a unifying framework for classical mechanics, geometric optics, and integrable systems, interweaving principles such as Maupertuis's least action, canonical formalism, and integral invariants. Yet, extending this theory to stochastic dynamicswhere noise disrupts deterministic structuresremains a profound challenge. This talk re-examines Jacobi's integration theory through a stochastic lens, synthesizing geometric, analytical, and hydrodynamic perspectives to construct a coherent framework for stochastic integrability and its applications.

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MS62

The Stochastic HamiltonJacobiBellman Theory on Jacobi Structures

As is well-known, Jacobi structures are the natural generalization of Poisson structure and in particular of symplectic, cosymplectic and LiePoisson structures. However, very interesting manifolds like contact and locally conformal symplectic manifolds are also Jacobi but not Poisson. In this talk, we use the global stochastic analysis tools, developed originally by Meyer and Schwartz, to give a strict mathematical definition of general stochastic Hamiltonian systems on Jacobi structures, and then present a stochastic HamiltonJacobiBellman theory which is regarded as an alternative method for formulating the dynamics. We highlight that some results in this talk is indeed a generalization of that in Bismut and Lazaro-Cami & Ortega, and some inspirations for the geometric HJ theory in stochastic settings should also go back to the deterministic works of Abraham Marsden and Carinena et. al.

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MS63

Insights From a Nanometric Model of Intracellular Calcium Cycling in Isolated Cardiomyocytes: The Role of RyR2 Regulation in the Prevention of Arrhythmogenic Waves

We show the results of a new detailed 3D in-silico model at the 100 nm scale of the calcium-cycling dynamics in isolated cardiomyocytes at electrotonic rest. The bi-compartimental model includes realistic distribution of RyR2 clusters and Sodium-Calcium exchangers, buffers and RyR2 regulation. Regarding this last feature, the model includes realistic regulation of the RyR2 by, both, Calmodulin (CaM) and Calsequestrin (CASQ), linking classic formulations of the literature with current knowledge on RyR2 binding sites for Ca-CaM and CASQ. The deterministic version of this model unveils the rol of this regulation in the propagation of calcium waves and its pro-arrhythmic effects. With RyR2 regulation, the cell remains in a stable but excitatory state where short transitory calcium waves are the natural healthy response to increases in the calcium load of the cell. Regulation failure of the CaM transforms the appearance of short transient calcium waves into larger waves with very large NCX extrusion and large associated pro-arrhythmic inward NCX current. We also show that the co-localization of Calsequestrin with the RyR2 is a key ingredient of healthy wave propagation. Without it, the system is not excitatory and, uniform wave-fronts are difficult to propagate. The system naturally evolves toward the spatial formation of domains with high cytosolic calcium concentration that only shrink due to a slow extrusion of calcium via NCX.

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MS63

2D and 3D Interactive, Real Time Simulations of Excitable Systems Using Gpu. Comparing Webgl, Webgpu and Metal

Many models of excitable systems, especially those used for complex biological dynamics such as in the case of heart and brain dynamics, require very large spatial domains and involve solving millions of coupled partial differential equations at each time step. As a result, exploring parameters and analyzing emerging behaviors across different spatial domain shapes and dimensions often necessitate supercomputers. However, over the past decade, GPUs in local laptops and PCs have enabled these large simulations to run locally and fast enough to allow real-time interaction. Several programming languages have emerged to support real-time simulations over large domains. Here, we present a comparison of these languages, detailing their simulation speeds and outlining the advantages and disadvantages of each.

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MS63

Optimizing Experimental Designs for Model Selection of Ion Channel Drug-Binding Dynamics

The rapid delayed rectifier current carried by the human Ether--go-go-Related Gene (hERG) channel is susceptible to drug-induced reduction which can lead to an increased risk of cardiac arrhythmia. Establishing the mechanism by which a specific drug compound binds to hERG can help to reduce uncertainty when quantifying pro-arrhythmic risk. In this study, we introduce a methodology for optimising experimental voltage protocols to produce data that enable different proposed models for the drug-binding mechanism to be distinguished. We demonstrate the performance of this methodology via a synthetic data study and extend this to trialling the method with real voltage clamp data.

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MS64

Rare Transitions in Noisy Heteroclinic Networks

We study white noise perturbations of planar dynamical systems with heteroclinic networks, in the limit of vanishing noise. We show that the probabilities of transitions between various cells that the network tessellates the plane into decay as powers of the noise magnitude, and we describe the underlying mechanism. A metastability picture emerges, with a hierarchy of time scales and clusters of accessibility, similar to the classical Freidlin-Wentzell picture but with shorter transition times. We discuss applications of our results to homogenization problems and to the invariant distribution asymptotics. At the core of our results are local limit theorems for exit distributions obtained via methods of Malliavin calculus. Joint work with Hong-Bin Chen and Zsolt Pajor-Gyulai.

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MS64

Analysing Dynamics Near Heteroclinic Networks

with a Projected Map

A heteroclinic cycle is a particular solution structure found in dynamical systems, typically composed of a collection of saddle equilibria and heteroclinic orbits connecting them in a cyclic manner. Trajectories near an attracting heteroclinic cycle visit all saddles in order, spending increasingly long periods of time near each saddle before making a rapid switch to the next one. Systems with heteroclinic cycles can be used to model intransitive interactions and intermittent phenomena. A heteroclinic network is a connected union of heteroclinic cycles. Trajectories near a heteroclinic network can exhibit complex dynamics. They may be attracted to one cycle within the network, possibly visiting a finite number of other cycles first, or they may be attracted to a larger subset of cycles of the network, visiting them in regular or irregular sequences. Regions of parameter space associated with the different asymptotic behaviour can form highly intricate patterns, including Farey-like concatenation. This talk will discuss how the general methodology for analysing heteroclinic cycles and networks, and how a particular piecewise-smooth map can be used to investigate the complex dynamics near heteroclinic networks.

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MS64

Aperiodic Behaviour Near the Rock-Paper-Scissors-Lizard-Spock Heteroclinic Network

The game of Rock-Paper-Scissors-Lizard-Spock is an extension of the well-know Rock-Paper-Scissors game, where now each strategy is dominant over two of the remaining four strategies, and is dominated by the remaining two. A differential equation model of the dynamics of five species with this set of competitive interactions contains a set of coupled heteroclinic cycles forming a heteroclinic network. In this talk I will show how the dynamics near this network can be described by a two-dimensional piecewise smooth map. The map contains a chaotic attractor, which is realized in the original flow as trajectories which approach the network whilst visiting an aperiodic sequence of equilibria.

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MS65

Clustering in Pure-Attention Hardmax Transformers and Its Role in Sentiment Analysis

Transformers are extremely successful machine learning models with poorly understood mathematical properties. In this talk, we rigorously characterize the asymptotic behavior of transformers with hardmax self-attention and normalization sublayers as the number of layers goes to infinity. By viewing such transformers as discrete-time dynamical systems describing the evolution of particles interacting in a Euclidean space, and thanks to a geometric interpretation of the self-attention mechanism based on hyperplane separation, we show that the transformer inputs asymptotically converge to a clustered equilibrium determined by special particles we call leaders. We leverage this theoretical understanding to solve a sentiment analysis problem from language processing using a fully interpretable transformer model, which effectively captures 'context' by clustering meaningless words around leader words carrying the most meaning.

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MS65

Mean-Field Control Barrier Functions: A Framework for Real-Time Swarm Control

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.

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MS65

Quantitative Propagation of Chaos for Non-Exchangeable Diffusions Via First-Passage Percolation

This talk discusses a non-asymptotic approach to mean field approximations for systems of n diffusive particles interacting pairwise. The interaction strengths are not identical, making the particle system non-exchangeable. The marginal law of any subset of particles is compared to a suitably chosen product measure, and we find sharp relative entropy estimates between the two. Building upon prior work in the exchangeable setting, we use a generalized form of the BBGKY hierarchy to derive a hierarchy of differential inequalities for the relative entropies. Our analysis of this complicated hierarchy exploits an unexpected but crucial connection with first-passage percolation, which lets us bound the marginal entropies in terms of expectations of functionals of this percolation process. Joint work with Daniel Lacker and Fuzhong Zhou.

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MS66

Inferring Networks of Chemical Reactions by Curvature Analysis of Kinetic Trajectories

Quantifying interaction network of chemical reactions allows efficient description, prediction, and control of a range of phenomena in chemistry and biology. The challenge lies in unambiguously assigning contributions to changes in rates from different interactions. Here we propose that the curvature change of kinetic trajectories due to a systematic, persistent perturbation of a node in a network can identify the coupling timescale, and thus its strength. Specifically, the coupling strength can be calculated as the ratio of the curvature change measured from the coupled node and the rate change of a perturbed node. We demonstrated the methodology with computational recovery of a large network with complex ordinary differential equations describing a network of Lorenz systems and experiments with electrochemical networks. The experiments show excellent network inference (without false positive or negative links) of various systems with large heterogeneity in local dynamics and network structure without any a-priori knowledge of the kinetics. The theory and the experiments also clarify the influence of local perturbations on response amplitude and time through network-wide up-regulation. A major advantage of our technique is its independence from hidden nodes. This makes it highly suitable for applications with high temporal and low spatial resolution data from interacting chemical and biochemical systems including neuronal activity monitoring with multi-electrode arrays.

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MS66

Divide and Conquer : Learning Chaotic Dynamical Systems with Multistep Penalty Losses

Forecasting high-dimensional dynamical systems is a fundamental challenge in various fields, such as geosciences and engineering. Deep Learning has emerged as a promising tool for forecasting complex nonlinear dynamical systems. However, classical techniques used for their training are ineffective for learning chaotic dynamical systems. In this work, we propose a novel training approach that allows for robust learning of such systems. Our method addresses the challenges of non-convexity and exploding gradients associated with training networks with underlying chaotic dynamics. The model predictions for such systems are split into multiple, non-overlapping time windows. In addition to minimizing deviations from the training data, the optimization further penalizes the discontinuities of the predicted trajectory between the intermediate states. Our proposed algorithm, denoted the Multistep Penalty(MP) method, is applied to chaotic systems such as the Lorenz system, KuramotoSivashinsky equation, the two-dimensional Kolmogorov flow, ERA5 reanalysis data, and ocean data. We also test it with several architectures like Neural ODE, Fourier Neural Operator, and UNet. It is observed that MP method provides viable performance for chaotic systems, not only for short-term predictions but also for preserving invariant statistics that are hallmarks of the chaotic nature of such systems.

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MS66

Lifelong Learning with Optimal Adaptive Tracking Control of Dynamical Systems

Lifelong learning (LL) is a machine-learning paradigm characterized by continual learning and positive knowledge transfer between tasks. In the context of optimal tracking control of dynamical systems, the task is to learn the optimal control policy. Controllers will therefore experience multiple tasks, i.e. be required to learn several different optimal control policies, when the system dynamics or the region of operation changes. Examples of scenarios where a controller may experience multiple tasks include: changing end effectors of a robot arm, a UAV used to transport packages of variable mass and moment of inertia, and tracking several distinct reference trajectories. While adaptive dynamic programming (ADP)-based control techniques that can continually learn from measured system data have already been developed, these controllers do not enable knowledge transfer between tasks. In particular, when they are exposed to multiple tasks neural network-based online ADP controllers often face the problem of catastrophic forgetting. This is where learning the new task erases critical information from previous tasks. In this work, we will discuss two classes of online LL methods, namely regularization and structural approaches that can be used to mitigate catastrophic forgetting and enable knowledge transfer between online control tasks. Finally, we will present the multitask performance of the LL-enabled optimal tracking controllers on both linear and nonlinear systems.

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MS66

Lifelong Context Recognition Via Online Deep Feature Clustering

Graph Neural Networks (GNN) have seen increased interest due to their fit with several types of real-world data, and the development of algorithms and hardware to better suit their computational demands. This paper will cover specialized cases for GNN in unsupervised learning, motivated by explanation capabilities.

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MS67

Beyond Imitation: Evolutionary Game Dynamics with Heterogeneous Learning Rules

A Tragedy of the Commons" refers to scenarios in which individuals acting according to their own self-interest leads to over-consumption and consequently the collapse of a shared common resource. They arise in numerous consequential real-world problems (ranging from climate change, traffic congestion, and epidemics) that pit myopic individual desires against collective benefits. A long-standing challenge is to understand the conditions under which such tragedies can be averted. Two primary approaches involve 1) devising incentive policies that discourage consumption behavior and 2) understanding how individuals make decisions over time, warranting the use of game-theoretic tools. A class of evolutionary game models known as feedback-evolving games has emerged as an effective framework to address these challenges. It considers a large population of individuals whose payoffs are endogenously coupled with a dynamically changing environmental state. In this talk, I will discuss recent results and opportunities for which feedback-evolving games can be extended along two important directions: 1) the impact of alternate agent learning rules that go beyond the usual imitation dynamics and 2) hierarchical decision-making interactions among multiple populations and shared environments.

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MS67

Artificial Fear to Enhance Adaptability in NMPC-Based Navigation

The development of intelligent robots capable of adapting to dynamic and unknown environments necessitates the integration of survival and self-preservation concepts. Traditional navigation methods, such as Artificial Potential Fields (APF) and Nonlinear Model Predictive Control (NMPC), rely on physical or kinematic models with manually tuned parameters. While effective in specific scenarios, these methods face significant limitations in generalizability due to their dependency on labor-intensive parameter tuning, particularly in complex environments. To address this challenge, we propose a novel approach leveraging artificial emotions, such as fear, to enhance robotic responses to unexpected or hazardous situations. Inspired by the neuroscientific dual-pathway model, we developed a fear-based control framework for adaptive navigation. The framework mimics the "Low Road" pathway by incorporating proxies for the amygdala, modeled as a reinforcement learning agent, and the brainstem, orchestrated through an NMPC. The amygdala dynamically adjusts NMPC parameters based on perceived fear, enabling rapid and context-aware responses. Simultaneously, the "High Road" pathway is modeled using a Large Language Model (LLM) to represent the cerebral cortex, enhancing higher-level trajectory planning by integrating contextual and visual information with advanced reasoning capabilities. Research conducted within the "FAIR" project, funded by Next-GenerationEU (PNRR PE00000013).

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MS67

Adaptive-Gain Control to Solve the Equilibrium Selection Problem in Population Games

We deal with the equilibrium selection problem, which arises whenever a controller wants to steer a population of individuals engaged in strategic interactions to a desired collective behavior. A poweful mathematical method to describe a population engaged in strategic interactions is by means of evolutionary game theory. The replicator equation has emerged as an elective tool to study the evolution of the collective behavior of the population. Hence, the equilibrium selection problem can be studied as a control problem for the replicator equation, which is ultimately a nonlinear ordinary differential equation. In the literature, this problem has been often takled using open-loop strategies, by designing the game is such a way that the desired equilibrium becomes globally attractive. However, the applicability of open-loop strategies is limited by the need of accurate a priori information on the game and by their scarce inherent robustness to uncertainty and noise. To overcome these limitations, we propose a closed-loop strategy in which we encapsulate an adaptive-gain control scheme within the replicator equation. For most classes of games we establish sufficient conditions to design a controller that guarantees convergence of the replicator equation to the desired equilibrium, requiring limited a-priori information on the game. This work was carried out within the FAIRFuture Artificial Intelligence Research and received funding from the Next-GenerationEU (PE00000013).

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MS68

Network Effects and Behavioral Feedback in Epidemics

In recent years, there has been renewed interest in the modeling, analysis and control of epidemics. The classic SIR model presents limitations due to its assumption of fully mixed and homogeneous population. It is essential to consider network effects to account for heterogeneity in susceptibility, infectivity and interactions. In addition, different behavioral changes of the individuals may influence the epidemic. This talk first focuses on analyzing the SIR model on a network of interacting subpopulations. These subpopulations consist of homogeneously mixed individuals with differing activity rates, disease susceptibility and infectivity. In contrast to the classic SIR model, we show that infection curves can be multimodal in the single node. With rank-1 interaction matrix, we provide sufficient conditions for this multimodality and establish an upper bound on the number of monotonicity changes in the node-level infection curve. Additionally, we characterize the system's asymptotic behavior, with explicit expressions for limit equilibrium points and conditions for their stability. The second part of the talk analyzes a deterministic SIR model in which the transmission rate depends on the system state, reflecting behavioral adaptations in response to the epidemic. Under general conditions, we prove that the infection curve is unimodal. We then solve an optimal control problem to minimize intervention costs while keeping the infection curve below a desired threshold.

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MS68

Networked Competitive Bivirus SIS Spread with Higher Order Interaction

This talk explores the simultaneous spread of two competing viruses over a network of population nodes by also accounting for the possibility of higher-order interactions (HOI). To this end, we consider a continuous-time time-invariant competitive bivirus networked susceptible-infectedsusceptible (SIS) HOI system. First, we show that, under the assumption that the hypergraph associated with the system is strongly connected, the model is strongly monotone. Subsequently, using the Parametric Transversality Theorem of differential topology, we show that, for generic parameter choices, the system admits only a finite number of equilibria, and that the Jacobian, evaluated at any equilibrium, is a nonsingular matrix. The aforementioned two findings together guarantee that the typical behavior of the model is convergence to some stable equilibrium point. The equilibria of this system are i) the disease-free equilibrium (DFE), ii) single-virus endemic equilibria, and iii) coexistence equilibria (where both viruses are present in separate fractions of a population node). We identify a parameter regime that admits the possibility of three equilibria (namely, the DFE, and two single-virus endemic equilibria) being simultaneously stable. We then provide sufficient conditions for the existence of a coexistence equilibrium, both for the same parameter regime as mentioned above, and for a different one.

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MS69

Adversarial Dynamics and Barriers in Operator Learning

Many modern systems are too complicated to analyze directly or lack clear models, driving significant interest in learning-based methods. A major challenge in these methods is dealing with nonlinearity. Koopman operators have emerged as a leading data-driven approach, as their spectral information provides a global linearization of nonlinear dynamics, allowing nonlinear analysis and control using linear techniques. However, learning these spectral properties has proven a significant challenge, with current algorithms facing issues such as lack of convergence. We address a key question: When can we reliably learn Koopman spectral properties from system data, and when is it impossible? To tackle this, we construct adversarial dynamical systems that reveal the first impossibility results in data-driven dynamical systems. These are universal across algorithms, independent of data quality or quantity, and not rare no randomized algorithm can succeed with more than 50% probability. Additionally, we identify when learning is possible and introduce optimal algorithms with built-in verification, overcoming issues in standard methods and ensuring convergence under broad conditions. Our results establish a classification framework for data-driven dynamical systems, extending beyond Koopman operators. This classification offers a unified perspective on methods and systematically shows when and how Koopman spectral properties can be learned.

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MS69

Entropic Transfer Operators

We propose a new concept for the regularization and discretization of transfer and Koopman operators in dynamical systems. Our approach is based on the entropically regularized optimal transport between two probability measures. In particular, we use optimal transport plans in order to construct a finite-dimensional approximation of some transfer or Koopman operator which can be analyzed computationally. We prove that the spectrum of the discretized operator converges to the one of the regularized original operator and report on three numerical experiments, including one based on the raw trajectory data of a small biomolecule from which its dominant conformations are recovered.

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MS69

Takens Meets Koopman: Linear Least Squares Prediction of Nonlinear Time Series

The least squares linear filter, also called the Wiener filter, is a popular tool to predict the next element(s) of time series by linear combination of time-delayed observations. We consider observation sequences of deterministic dynamics, and ask: Which pairs of observation function and dynamics are predictable? If one allows for nonlinear mappings of time-delayed observations, then Takens' well-known theorem implies that a set of pairs, large in a specific topological sense, exists for which an exact prediction is possible. We show that a similar statement applies for the linear least squares filter in the infinite-delay limit, by considering the forecast problem in an invertible ergodic-theoretic setting and the Koopman operator on square-integrable functions.

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MS69

Reconstruction of Network Dynamics from Partial Observations

We address the extent to which the time series at one node of a dynamical network can be successfully reconstructed by measuring at another node, or subset of nodes, corrupted by observational noise. We will assume the dynamical equations of the network are known, and that the dynamics are not necessarily low-dimensional. The case of linear dynamics is treated first, and leads to a definition of observation error magnification factor (OEMF) that measures the magnification of noise in the reconstruction process. Subsequently, the definition is applied to nonlinear and chaotic dynamics. Comparison of OEMF for different target/observer combinations can lead to better understanding of how to optimally observe a network. As part of the study, a computational method for reconstructing time series from partial observations is presented and analyzed.

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MS70

Existence and Stability of Localized Patterns : a Computer-Assisted Proof

In this talk, I will present a computer-assisted approach for constructive existence proofs of localized solutions. The method is based on the numerical construction of an approximate solution u_0 using Fourier series and on an approximate inverse of the linearization at u_0. The approximate solution and the approximate inverse serve for the construction of a Newton-like fixed point operator. Thanks to the use of rigorous numerics, we are able to verify that such an operator falls into the scope of the Banach-fixed point theorem, leading to the existence of a true solution. In particular, I will show that this setup provides a posteriori control on quantities of interest, such as the spectrum of the linearization, enabling the verification of (at least spectral) stability. This is joint work with Jean-Philippe Lessard and Jean-Christophe Nave.

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MS70

On the Spectrum of the Front in a Predator-Prey Model

We consider a predator-prey model with diffusion. Depending on the parameter regime, phenomenologically different types of fronts exist in this model. In particular, in the situation when the prey diffuses at the rate much smaller than that of the predator, there exists a parameter regime when the underlying dynamical system in a singular limit is reduced to a scalar Fisher-KPP equation. The process of the reduction consists of taking limits with respect to two parameters. In this presentation, the stability of these fronts is discussed. In particular, it is focused on obtaining uniform (in the singular parameters) bounds on the discrete spectrum.

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MS70

Exponential Dichotomies and Their Application in Higher-Dimensional Spatial Dynamics for Elliptic PDEs

Exponential dichotomies, when they exist, provide powerful information about the structure of bounded solutions even in the case of an ill-posed evolutionary equation. The method of spatial dynamics, in which one views a spatial variable as a time-like evolutionary variable, allows for the use of classical dynamical systems techniques, such as exponential dichotomies, in broader contexts. This has been utilized to study stationary solutions of PDEs on spatial domains with a distinguished unbounded direction (e.g. the real line or a channel of the form $\mathbb{R}\Omega$). Recent work has shown how to extend the spatial dynamics framework to elliptic PDEs posed on general multi-dimensional spatial domains. In this talk we show that, in the same context, exponential dichotomies do exist, thus allowing for their use in future analyses of coherent structures, such as spatial patterns in reaction-diffusion equations on more general domains.

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MS70

Radius Selection for Amphiphilic Structures

Amphiphilic copolymers, molecules that share the ability to form bonds with both water and fats, are the basic building blocks of biological membranes. Recent technological advances have also shown that synthesizing such compounds can be incredibly useful in biomedical engineering applications. This utility resides their ability to self-assemble out of their constituent parts by minimizing an interaction energy, and the variety of morphologies of the resulting structures. In this work we analyze a phenomenological model for amphiphilic copolymer self-assembly, a functionalized Cahn-Hilliard type nonlocal equation introduced in [Glasner. SIAM J. Math. Anal (2017)]. In such a model, copolymer structures correspond to stationary solutions solve a fourth order partial differential equation. We prove rigorous existence results for radially symmetric structures in 1, 2 and 3 spatial dimensions using a geometric singular perturbation theory approach. Complicating the analysis is the fact that the partial differential equations in question are non-autonomous in dimensions 2 and 3 due to the presence of the radial Laplacian. Despite this we are able to prove the existence and bifurcation of radially symmetric patterns and confirm existing formal expressions for the selected structure radius [Glasner. Phys Rev. E (2019)].

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MS72

A Computer-assisted Proof of Stochastic Resonance

I will present some ideas to rigorously quantify the phenomenon of stochastic resonance for the noisy Duffing oscillator. To this end, we lay some mathematically rigorous foundations for the resolution of differential equations with respect to semi-classical bases, namely FreudSobolev polynomials. This leads us to make progress on various problems in Numerical Analysis such as Sobolev orthogonal polynomials and Painlev equations. Brought together, these ingredients allow us to quantify the compactness of Sobolev embeddings on Freud-weighted spaces and finally resolve some differential equations in this topology.

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MS72

Global Dynamics of ODEs

I will discuss an algorithmic approach for identifying the global dynamics of multi-parameter systems of ODEs and focus on the following points. (1) I will argue that a non-traditional notion of solution is necessary and suggest one based on order theory and algebraic topology. (2) I will discuss the philosophy of the approach we are taking. (3) I will introduce a specific family of differential equations for which we can produce a rigorous combinatorial/algebraic topological characterization of the dynamics, a well defined finite decomposition of parameter space, and provide results from sample computations.

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MS72

Computer-Assisted Proofs Of Existence Of Fiberwise Hyperbolic Invariant Tori In Quasi-Periodic Systems Via Fourier Methods

The goal of this paper is to provide a methodology to prove the existence of (fiberwise hyperbolic) real-analytic invariant tori in real-analytic quasi-periodic skew-product dynamical systems that present nearly-invariant tori of the same characteristics. The methodology was based on the application of a Newton-Kantorovich theorem whose hypotheses were tested using Fourier analysis methods for a numerical approximation of the parameterization of an invariant torus.

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MS72

Spectral Stability of the Swift-Hohenberg Equation with Computer Assisted Proofs

The Swift-Hohenberg equation is a partial differential equation noted for its use in modeling pattern formation. In this talk we consider the problem of determining the spectral stability of standing pulse solutions. A difficulty in determining spectral stability is that the point spectrum can be difficult to compute, making it challenging to see if there are any positive eigenvalues. To deal with this, we count a related object called conjugate points, which have a 1-1 correspondence with unstable eigenvalues. We discuss the numerics involved in counting conjugate points and how computer assisted proofs can be applied to give a rigorous proof of the spectral stability/instability of a pulse solution.

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MS73

Triadic Interactions Induce Dynamical Functional and Topological Patterns in Brain Networks

Triadic interactions, involving a set of nodes influencing interactions between others, are seen in systems like the brainwhere glia modulate neuron signals or interneurons control presynaptic effectsand in ecosystems, where species impact interactions among others. On random graphs, recent studies show that triadic percolation turns percolation into a dynamic process with chaotic transitions in the giant component's size. However, real-world triadic interactions are often local, occurring in spatially embedded networks. We demonstrate that triadic interactions on spatial networks lead to complex, spatio-temporal changes in the giant component, resulting in unique triadic percolation patterns with distinct topologies. Using topological data analysis, we classify these patterns (e.g., stripes, octopus, small clusters) and evaluate their entropy and complexity. Furthermore, we reveal the multistable nature of these percolation dynamics and map a phase diagram of the model. Our findings suggest that with spatial triadic interactions, the giant component adopts a dynamic topology, offering a framework to model scenarios like time-dependent brain networks.

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MS73

Synchronisation Is a Higher-Order Effect in Hypernetwork Systems

We introduce a new framework for describing ODEs that model coupled cell systems with higher-order interactions. As with classical networks, we may consider invariant synchrony spaces and generalise these to hypergraph fibrations. It is known that in the classical network setting, the linear systems determine all robust synchronisation patterns. Surprisingly, we find that this is not the case for hypernetworks. Instead, one has to consider nonlinear terms up to some fixed degree, which can be bounded by a formula involving the order of the hypernetwork. We give a class of examples for which this degree is optimal. This means that some polydiagonal spaces may fail to be invariant only due to the high-order terms in the system. As a direct result, we find intriguing generic bifurcation scenarios, where synchrony between two nodes is broken at an unusually slow rate in the bifurcation parameter. We give examples and rigorous results for these so-called "reluctant synchrony breaking" bifurcations. This is joint work with Sren von der Gracht and Bob Rink.

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MS73

Higher-Order Kuramoto Models Between Brains, Basins, and Renormalization

The dynamics of brain networks are inherently complex, with interactions extending beyond simple pairwise connections. Simplicial Kuramoto models offer a framework to capture these higher-order interactions, reflecting the intricate synchronization patterns observed in brain activity. Here I will focus on applying renormalization techniques to simplicial Kuramoto models, revealing how hierarchical organization and scale-dependent behavior emerge in these systems. I will discuss recent findings on the impact of renormalization on higher-order synchronization properties and confront these insights with neuroimaging data. By comparing theoretical predictions to empirical brain dynamics, we gain new perspectives on multi-scale synchronization and functional organization in neural systems, enhancing our understanding of how higher-order interactions shape cognitive and behavioral outcomes.

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MS73

Opinion Dynamics with Polyadic Interactions

In mathematical models of opinion dynamics, individuals have opinions and they can potentially compromise their opinions when they interact with each other. Depending on the model, these opinions can take either discrete or continuous values. In this talk, I will discuss opinion dynamics in polyadic networks, in which three or more individuals can interact with each other simultaneously. I will discuss both bounded-confidence opinion models and other opinion models, and I will highlight qualitative behavior that differs between polyadic networks and networks with only dyadic (i.e., pairwise) interactions.

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MS74

Analysis of Lobe Dynamics in a Higher-Dimensional Map

Spacecraft trajectory design utilizes dynamical structures based on Poincare maps in the restricted three-body problem, one of the Hamiltonian systems. The dynamical structures in the planar problem are represented by a two-dimensional Poincare map and investigated well in literature. For higher-fidelity models such as the spatial problem and the restricted four-body problem, however, higher-dimensional Poincare maps are required to represent their dynamical structures. As a first step, this study aims to analyze dynamical structures in a three-dimensional map called the ABC map. An invariant curve in the ABC map is first computed based on its invariance condition. The rotation number of this curve is oscillating, so we develop the computational method for this type of invariant curve. Next, the parameterization method for invariant manifolds is applied to exactly identify the stable and unstable manifolds associated with the obtained invariant curve. The oscillating rotation number of this invariant curve is incorporated into the manifold calculation by modifying the existing parameterization method. This parameterization helps to identify dynamical structures enclosed by these manifolds. In numerical examples, we investigate the dynamical structures called lobes in the ABC map.

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MS74

On the Arnold Diffusion Mechanism in Medium Earth Orbit

Space debris mitigation guidelines represent the most effective method to preserve the circumterrestrial environment. Among them, end-of-life disposal solutions play a key role. In this regard, a growing effort is devoted to exploit natural perturbations to lead the satellites toward an atmospheric reentry, reducing the cost. In the case of the MEO region, home of the navigation satellites, the main driver is the gravitational perturbation due to the Moon, that can increase the eccentricity in the long term. In this work, we show how an Arnold diffusion mechanism can trigger this effect. First, the Moon is assumed to lay on the ecliptic plane and periodic orbits and associated stable and unstable invariant manifolds are computed for various energy levels, in the neighborhood of a given resonance. Along each invariant manifold, the eccentricity increases, achieving its maximum at their first intersection. This growth is, however, not sufficient to achieve reentry. By moving to a model that considers the inclination of the Moon, the problem becomes non-autonomous and the satellite can move along different energy levels. Under the ansatz of transversality of the stable and unstable manifolds in the autonomous case, checked numerically, PoincarMelnikov techniques are applied to show how the Arnold diffusion can be attained, by constructing a sequence of homoclinic orbits that connect invariant tori at different energy levels on the normally hyperbolic invariant manifold.

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MS74

On the Symplectic Geometry of the Circular Restricted Three-Body Problem

In this talk, I will briefly touch upon some of the recent developments on the theoretical aspects of the classical CR3BP, coming from the modern approach from symplectic geometry, and speculate on expected applications. Based on work with Otto van Koert, Urs Frauenfelder, Cengiz Aydin, Dayung Koh.

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MS74

Methods in Kam Theory for Lagrangian Tori in Quasi-Periodically Time-Dependent Hamiltonian Systems

In this work, we discuss a KAM theorem in an a-posteriori format that employs the parameterization method to locate invariant tori in autonomous Hamiltonian systems with periodic or quasi-periodic time dependence and multiple external frequencies. By introducing a variable $\phi \in \mathbb{T}^\ell$, we expand the phase space to $\mathcal{M} \times \mathbb{T}^\ell$, where $\mathcal{M}$ is an open subset of $\mathbb{R}^{2n}$. This approach reduces the problem's dimensionality from $2(n+l)$ to $2n$. Using a quasi-Newton method, we refine an initial parameterization that approximately satisfies the invariance equation. This method reduces the error quadratically with each iteration, converging to a torus within a complex strip of size ρ, under Diophantine and non-degeneracy conditions. This ensures the persistence of invariant tori if the product $\gamma^{-4}\rho^{-4\tau}$ and the error remain sufficiently small, thereby establishing their existence in Hamiltonian systems. This numerical method is effective for computing invariant manifolds, and we illustrate its application in two physical models.

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MS75

Molecular Mechanisms in Actively Driven Passively Crosslinked Microtubule Pairs

We apply stochastic modeling to interpret in vitro experiments involving microtubules interacting with the passive crosslinker PRC1 while being crowdsurfed by kinesin in a gliding assay configuration. When an antiparallel pair of microtubules is crosslinked by PRC1, the kinesin slides the microtubules apart while the PRC1 resists this separation. We examine the molecular-scale mechanisms responsible for the two distinct dynamical modes of resistance which are observed in experiments.

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MS75

Modeling Mechanisms of Microtubule Behavior and Polarity in Neurons

In neurons, the stability and polarity of the microtubule cytoskeleton is required for long-range, sustained transport within the cell. In fruit fly neurons, the healthy microtubule cytoskeleton is comprised of tubulin protein and is stable with a particular orientation. However, when injured, these microtubules are dynamic, rearrange their orientation, and formation of new microtubules (called nucleation) is upregulated. It is unknown what mechanisms are involved in this balance between dynamic rearrangement and sustained function. Using experimental data and a stochastic mathematical model, we seek to understand how nucleation can impact microtubule dynamics in dendrites of fruit fly neurons. In the stochastic model, we assume two mechanisms limit microtubule growth: limited tubulin availability and the dependence of shrinking events on microtubule length. To better understand our stochastic model, we develop a partial differential equation (PDE) model that describes microtubule growth and nucleation dynamics, and we compare analytical results to results from the complex stochastic model. Insights from these models can then be used to understand what mechanisms are used organize into polarized structures in neurons, and how microtubule dynamics, like nucleation, may impact cargo localization post-injury.

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MS75

Different Relative Scalings Between Transient Forces and Thermal Fluctuations Tune Regimes of Clustering Dynamics

Biological systems under the influence of microscale active agents such as proteins are frequently modeled using stochastically-switching forces as the agents shift between different states. These rapidly switching forces are often on timescales faster than the time to reach thermal equilibrium, thus the system is in a constant state of disequilibrium. In one example system, a bead-spring polymer model of chromosomes with additional crosslinking stochastically-switching forces, long-lived stable condensed clusters of beads are observed consistent with experimental results. The lifetime of these clusters is linked to the stochastic switching rate which acts like an effective temperature: rapid switching produces low-temperature-like stable clusters, slow switching produces high-temperature-like amorphic arrangements, and intermediate switching times allow for dynamic clusters with beads exchanging between clusters.I will derive an effective energy or quasipotential for the system, showing that different limits concerning the two noise sources (randomly switching protein binding forces and thermal noise) produce different predictions for the metastable transition times between clusters.

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MS76

Data Assimilation and Uncertainty Quantification in Cortical Models

This talk presents a framework for forward uncertainty quantification and data assimilation problems in spatially-extended neurobiological networks, for which we take neural fields as a prototype. Large-scale brain simulations of such models are currently performed heuristically, and the numerical analysis of these problems is largely unexplored. In the first part of the talk I will summarise recent developments for the rigorous numerical analysis of projection schemes for deterministic neural fields, which sets the foundation for developing Finite-Element and Spectral schemes for large-scale problems. The second part of the talk will discuss the case of networks in the presence of uncertainties modelled with random data, in particular: random synaptic connections, external stimuli, neuronal firing rates, and initial conditions. Such problems give rise to random solutions, whose mean, variance, or other quantities of interest have to be estimated using numerical simulations. In addition to this forward Uncertainty Quantification problem, I will also present results of an inverse problem in which cortical data is used to infer parameter and states of the neural field model. This talk presents joint work with Francesca Cavallini (VU Amsterdam), Svetlana Dubinkina (VU Amsterdam), Gabriel Lord (Radboud University), and Khadija Meddouni (Radboud University).

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MS76

Inhibitory Control of Traveling Cortical Waves

We develop a spiking one-dimensional network of neurons to explore the reliability and control of evoked waves and compare this to a cortical slice preparation where the excitability can be pharmacologically manipulated. To gain further insight into the mechanisms of propagation and transitions to pathological behavior, we derive a mean-field model for the synaptic activity. We analyze the mean-field model and a piece-wise constant approximation of it and study the stability of the propagating waves as spatial and temporal properties of the inhibition are altered. We show that that the transition to seizure-like activity is gradual but that the loss of propagation is abrupt and can occur via either the loss of existence of the wave or through a loss of stability leading to complex patterns of propagation

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MS76

Traveling waves of neural activity shape computation across the brains maps of sensory space

New technologies allow recording across single regions of neocortex with high spatial and temporal resolution. By analyzing recordings of spontaneous and stimulus evoked activity in single regions of the visual system, we have found that spontaneous and stimulus-driven waves of neural activity travel over these networks, sparsely modulating the spiking activity of the local network as they pass. The waves represent changes in the moment-by-moment activity state of these networks, which in turn directly shapes neuronal responses to incoming visual input and causes measurable effects in visual perception. Each region in the visual system contains a complete map of visual space, so that neighbouring inputs in visual space are mapped to nearby patches of neurons. What computations can be done by nTWs traveling over this map of visual space? We have developed a neural network model in which a few input frames from a learned movie trigger complex wave patterns that drive accurate predictions many movie frames into the future [Benigno et al., Nature Communications, 2023]. Predictions in this network demonstrate nTWs can play an essential computational role in sensory processing, by embedding continuous spatiotemporal structures over retinotopic maps. These results can be understood through a more general framework for studying computation with spatiotemporal dynamics in topographically organized recurrent neural networks [Budzinski*, Busch* et al., Communications Physics, 2024].

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MS76

Hidden Spirals in Human Local Field Potentials

Traveling oscillatory (phase) wave are commonly observed in multi-electrode recording in the brains of many species including humans. In collaboration with the Jacobs lab, we have obtained local field potential recordings from human subjects doing 8 cognitive tasks. The recordings consist of patterns of phase on a square array of electrodes. Statistical methods were used to identify epochs where the patterns were stationary. We hypothesized that the patterns could be described as phase-locked solutions to a network of locally coupled oscillators:

$$\theta_i' = \omega_i + \sum_{j \in N(i)} H(\theta_j - \theta_i)$$

We developed an optimization method to choose the local intrinsic frequencies, ω_i and the interaction function, $H(\phi)$ to fit the patterns and assure that the patterns were stable. We next hypothesized that the patterns were the result of the local frequency differences combined with ongoing activity due solely to the connectivity and the interaction function. To reveal this underlying activity, we gradually flatten the frequencies until all oscillators are identical. In some fraction of the recordings were able to find hidden spiral waves and that these spiral waves were associated with some cognitive tasks but not with others.

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MS77

Programming the Dynamical Algorithmic Subspaces and Model Manifolds of Reservoir Computers

Reservoir computing has emerged as a ubiquitous paradigm for performing complex temporal computations. One particularly impressive feature of reservoir computers (RCs) is inferencethe ability to accurately forecast new time-series datathereby demonstrating an understanding of the underlying equations that generated the data. How do we make exact this notion of understanding in the language of dynamical systems? Can we engineer this understanding to design RCs that run custom algorithms, thereby bringing reservoir computing closer to real computers? In this talk, I will first demonstrate a powerful analytical mechanism used by RCs to model the generative equations of data. Then, I will demonstrate how to analytically decompose RCs to decode this model from trained RCs, and how to simply design the interactions between RC units to program our own dynamical models and algorithms into the subspace of RCs. Finally, I will discuss some current work on traversing the model manifolds of RCsthe nonlinear geometry of RC parameters that perform the same computations with different weightsto define families of functionally equivalent RCs, and RC compositionalityhow to construct RCs with complex functions from those with elementary functionsto compose complex RC programs. The eventual goal is to transform RCs from computational devices into fully-fledged analog computers.

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MS77

Machine-Learning Prediction of Tipping with Applications to the Atlantic Meridional Overturning Circulation

Anticipating a tipping point, a transition from one stable steady state to another, is a problem of broad relevance due to the ubiquity of the phenomenon in diverse fields. The steady-state nature of the dynamics about a tipping point makes its prediction significantly more challenging than predicting other types of critical transitions from oscillatory or chaotic dynamics. Exploiting the benefits of noise, we develop a general data-driven and machine-learning approach to predicting potential future tipping in nonautonomous dynamical systems and validate the framework using examples from different fields. As an application, we address the problem of predicting the potential collapse of the Atlantic Meridional Overturning Circulation (AMOC), possibly driven by climate-induced changes in the freshwater input to the North Atlantic. Our predictions based on synthetic and currently available empirical data place a potential collapse window spanning from 2040 to 2065, in consistency with the results in the current literature.

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MS77

Minimal Reservoir Computing for Weakly and Strongly Nonlinear Time Series

The traditional setup of reservoir computing (RC) uses random matrices to define the underlying network and the input layer that transforms the input data to input signals in the reservoir. Here, we show that a few simple modifications, which eliminate randomness and minimize computational resources, lead to significant and robust improvements in short- and long-term predictive performance. We first introduce block-diagonal reservoirs, which implies that a reservoir can be composed of multiple smaller reservoirs. In a second step the non-linear activation function at the nodes can be dispensed with if the non-linear step in the analysis chain is shifted to the output layer. This means that not only the reservoir echo but also its higher powers are used to optimize the output weights. The input weights are determined according to well-defined rules. Any random initialization has thus been eliminated in this approach. By varying the remaining four hyperparameters, it is now possible to systematically investigate the transition from a linear, disjunct mapping of the input data to the output data to a combined nonlinear one. It is investigated how the prediction performance varies during this transition. The results are interpreted with respect to minimal requirements of RC for a proper prediction of weakly and strongly nonlinear time series. These results can guide the way towards explainable RC, where the prediction process becomes nearly fully transparent.

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MS77

Stabilizing Machine Learning Prediction of Dynamics: Novel Noise-Inspired Regularization Tested with Reservoir Computing

Recent work has shown that machine learning (ML) models can skillfully forecast the dynamics of unknown chaotic systems. Short-term predictions of the state evolution and long-term predictions of the statistical patterns of the dynamics (“climate’) can be produced by employing a feedback loop, whereby the model is trained to predict forward only one time step, then the model output is used as input for multiple time steps. This feedback can potentially result in artificially rapid error growth (“instability’). One established mitigating technique is to add noise to the ML model training input. Based on this technique, we formulate a new penalty term in the loss function for ML models with memory of past inputs that *deterministically* approximates the effect of many small, independent noise realizations added to the model input during training. We refer to this penalty and the resulting regularization as Linearized Multi-Noise Training (LMNT). We systematically examine the effect of LMNT, input noise, and other established regularization techniques in a case study using reservoir computing to predict the spatiotemporal chaotic Kuramoto-Sivashinsky equation. We find that reservoir computers trained with noise or with LMNT produce climate predictions that appear to be indefinitely stable and have a climate very similar to the true system, while the short-term forecasts are substantially more accurate than those trained with other regularization techniques.

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MS78

Causal Diffusion Components: Discriminating Predictive Features

We exploit reproducing kernel Hilbert spaces (RKHS) in order to cleanly represent causal states as geometric points, as well as to easily infer that representation from data. We further refine the method by encoding the causal states into a few number of coordinates using diffusion maps. These causal diffusion components encode the information needed to statistically discriminate between future behaviors. The first of these components encode most of the information, with decreasing gains as more components are added. Intuitively, this can be seen as analogous to a non-linear principal component analysis, but based on predictive information instead of variance. We demonstrate the use of the causal diffusion components on four distinct examples, including both simulated and real experimental data of various types and dimensionality. Practically, representing the causal states in these reduced dimension spaces highlights the hidden geometric predictive stucture of a process, showing constraints in its evolution, and patterns such as anomalies in the data. Compared to alternative machine learning approaches, our method requires only a small number of parameters. These are mostly the characteristic scales for analyzing each data source and for the causal relationships in time.

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MS78

Hierarchical Epsilon-Machine Reconstruction

I will define and then show how to discover hierarchical structure embedded in complex dynamical systems.

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MS78

How Well do Neurons, Humans, and Artificial Neural Networks Predict?

Sensory prediction is thought to be vital to organisms, but few studies have tested how well organisms and parts of organisms efficiently predict their sensory input in an information-theoretic sense. In this talk, we report results on how well cultured neurons ("brain in a dish") and humans efficiently predict artificial stimuli. We find that both are efficient predictors of their artificial input. That leads to the question of why, and to answer this, we study artificial neural networks, finding that LSTMs show similarly efficient prediction but do not model how humans learn well. Instead, it appears that an existing model of cultured neurons and a model of humans as order-R Markov modelers explain their performance on these prediction tasks.

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MS79

Insights into the Latent Reservoir Via Post-Treatment HIV Viral Dynamics Modeling

Antiretroviral therapy (ART) effectively controls HIV infection, suppressing HIV viral loads to levels undetectable by commercial tests. While typically suspension of therapy is rapidly followed by rebound of viral loads to high, pre-therapy levels, observations from the last decade give nuance to that statement: in a small fraction of cases, rebound may be delayed by months, years, or even possibly, permanently. We will discuss modeling to investigate that heterogeneity in outcome of treatment suspension, focusing on time to viralrebound. We will first discuss our data-validated, mechanistically-motivated survival function for time-to-rebound using time-inhomogeneous branching processes. We show good agreement with data for both rapid and significantly delayed viral rebound. We will then use this model to characterize the impact of covariates such as treatment initiation time and pre-ART drug regimen on time to rebound, and end by discussing implications of our observations on latent reservoir dynamics.

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MS79

Mathematical Modeling of Prolonged SARS-CoV-2 Infection

SARS-CoV-2 infections can persist in severely immunocompromised individuals for months or even years, resulting in prolonged, unchecked viral evolution. Examples of significant within-host viral evolution marked by mutations congruent with variants of concern have been reported in this population. From both a clinical care and public health perspective, it is essential to understand the factors driving these infections, including within-host evolution, and identify optimal treatment strategies. Towards this end, we have developed an ordinary differential equation model for within-host dynamics of SARS-CoV-2 infection and calibrated this to longitudinal viral load data. We further developed a stochastic model that combines viral and immune kinetics with a branching process describing viral mutation. We calibrated the evolutionary model to paired viral load and sequencing data from both acute and prolonged infections in people living with HIV. We have identified conditions necessary for prolonged infection to occur and assessed the impact of viral population dynamics on viral diversity. We will also discuss ongoing work incorporating selective pressures, including antiviral treatment and resistance, into the modeling framework.

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MS79

Modeling HIV Treatments: How Latency-Reversing Agents and Immune Modulators May Facilitate a Functional Cure

In this talk, I will present recent modeling studies that examine the effects of latency-reversing agents (LRAs) and immune modulators on HIV rebound dynamics following the interruption of antiretroviral therapy. In their seminal work, Conway and Perelson developed a viral dynamics model that describes how HIV rebound dynamics are determined by the size of the latent reservoir and the immune response. Building upon their work, we test different hypotheses regarding the primary mechanisms of action for drugs that either reduce the latent reservoir or enhance the immune response. We developed numerous variations of the Conway and Perelson model and fitted them to viral load data from multiple macaque studies. The best-fitting models accurately recapitulate the observed viral rebound dynamics and offer explanations for the diverse patterns of viral resurgence. Collectively, these models enhance our qualitative and quantitative understanding of how LRAs and immune modulators can be combined to facilitate a functional cure.

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MS79

Multiscale Models of Hepatitis B Virus Infection

More than 250 million people are chronically infected with hepatitis B virus (HBV) worldwide. Although there is an effective vaccine, there are still 1.2 million new infections per year, and no cure has been developed, leading to more than 1 million HBV-related deaths annually. HBV has a complex intracellular lifecycle, with a covalently closed circular DNA (cccDNA) template in the nucleus, which is difficult to eliminate. In addition, it is hard to assess the effectiveness of therapy in eliminating cccDNA since the site of replication, the liver, is not easily accessible. We have been developing multiscale dynamical models of HBV that include both liver and blood, and a detailed representation of the HBV lifecycle. By fitting these models to data from treatment with approved reverse transcriptase inhibitors and from phase I trials of capsid assembly modulators, we estimate the effectiveness of the drugs and identify the physiological mechanisms that drive the biphasic decline in HBV DNA and RNA. Moreover, using agent-based models of infection in the liver, we link treatment-based decay in HBV in the blood to the changes in the proportion of infected hepatocytes, the proportion of infected hepatocytes transcriptionally silent, and the fraction of hepatocytes transcribing from cccDNA vs. integrated DNA. We are using these models to help us understand the details of the HBV lifecycle and how these determine the quantitative observations on the effects of treatment.

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MS80

Asymptotic Analysis for the Solutions of Perturbed HamiltonJacobi Equations and Its Applications

We are concerned with a new perturbation problem for convex Hamilton-Jacobi equations. This perturbation problem explores the combined effects of both the vanishing discount process and potential perturbations, leading to a new selection principle that extends beyond the classical vanishing discount approach. As applications, a new linear operator will be introduced, which thereby provides new insights into the variational construction and characterization of viscosity solutions.

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MS80

Singular Dynamics for Discrete Weak K.A.M. Solutions of Exact Twist Maps

For any exact twist map f and any cohomology class $c \in \mathbb{R}$, let u_c be any associated discrete weak K.A.M. solution, and we introduce an inherent Lipschitz dynamics Σ_+ given by the discrete forward Lax-Oleinik semigroup. We investigate several properties of Σ_+ and show that the non-differentiable points of u_c are globally propagated and forward invariant by Σ_+. In particular, such propagating dynamics possesses the same rotation number $\alpha'(c)$ as the associated Aubry-Mather set at cohomology class c. As an application, a detailed exposition of the corresponding Arnaud's observation in 2011 is then provided via Σ_+. Furthermore, we construct and analyze the corresponding dynamics on the full pseudo-graphs of discrete weak K.A.M. solutions. This is a joint work with Jianxing Du.

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MS80

A Parameterization Method for Quasi-Periodic Systems with Noise

We study invariant manifolds for a class of quasi-periodically forced systems with stochastic noise. These systems are skew-product systems driven by small perturbations. The existence of invariant manifolds is established by developing a parameterization method in random setting and applying fixed point theorem in Banach spaces. Based on this, we describe how to compute the statistics of the invariant manifolds and Lyapunov exponents in stable and unstable directions.

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MS81

Comparison of Electrogram Signal Processing Indices for Mapping Atrial Fibrillation Dynamics and for Predicting Ablation Outcome

Background: Mapping of atrial fibrillation (AF) is often proposed to identify targets beyond pulmonary vein isolation (PVI). However, AF mapping shows conflicting and variable results across clinical studies. One major question is whether various proposed mapping indices indicate similar physiology or co-localize in spatial regions. Few studies have addressed these issues. Objectives: We studied if electrogram-derived AF indices correlate between each other and quantify similar spatial dynamics. We further studied if some AF indices predict ablation outcome better than the others, and if there is a link between AF indices and patient phenotypes. Methods: We studied 561 patients from the Stanford AF ablation registry (66+/-10y, 28% women, 67% non-paroxysmal AF) in whom unipolar electrograms (EGMs) were studied for > 30 seconds for the following AF mapping indices: (1) voltage; (2) repetitive spatial activity (REACT), (3) dominant frequency (DF), (4) rotational activity (phase singularities, PS density), and (5) cycle length (CL). In a separate dataset, we additionally studied bipolar AF indices of (6) EGM dispersion, and (7) fractionation (CFAE). Results will be presented at the conference.

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MS81

Intercalated Disk Ion Channel and Connexin Distribution Controls Tissue Conduction Velocity and Local Calcium Currents

The intercalated disk (ID) is the specialized cellular structure that connects cardiomyocytes. Electrogenic proteins are known to be preferentially located at the ID, such as the voltage-gated sodium channel (NaV1.5), inward-rectifying potassium channel (Kir2.1), sodium-potassium ATPase (NKA) and the L-type calcium channel (Cav1.2). Experimental evidence shows that modifing ID properties alters conduction, and that perturbed structures are found in patients with cardiac arrhythmias. In our previous work, we have shown that chamber-specific ID structures and changes in intermembrane distance lead to changes in tissue level conduction velocity. Here, we expand our model to include the spatial distribution of ion channels as well as representations of GJs within the ID. We find that concentrated Na+ channels or GJs lead to reduced conduction velocity at the tissue level. Further, we track local Na+, K+, Ca2+ and anion concentrations in the restricted extracellular space (or ID cleft). This allows us to make a novel observation: the previously observed Na+ depletion in the cleft leads to a compensatory influx of Ca2+, which in turn drives a significant increase in ID calcium current. Our results show that local ion channel clustering can regulate cardiac conduction. Moreover, the interplay between ion channel localization and ion concentration dynamics suggests a novel mechanism to ensure adequate calcium concentration within the ID-adjacent cellular region.

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MS81

Sensitivity of Observability Values for a Cardiac Ionic Model

Alternans a beat-to-beat (period-2) alternation in the electrical waves that govern contractions in the heart. Possible causes of alternans include instabilities in either the cellular membrane potential dynamics or the intracellular calcium dynamics, respectively leading to either voltage-driven or calcium-driven alternans. At present, little is known about the impact of alternans mechanisms on the performance of data assimilation algorithms. In response, in past studies, we applied computational methods from control theory to the Shiferaw-Sato-Karma (SSK) nonlinear ODE model of alternans. Specifically, we computed a control-theoretic model property called observability, which indicates whether dynamical modes can be reconstructed from measured variables. In our previous work, we did not explore whether the results were sensitive to perturbations in scaling matrices that were used to nondimensionalize the model. In the present study, we computed sensitivity ratios for observability values in response to one-at-a-time perturbations in scaling matrix parameters. The observability values were typically found to have low to moderate sensitivity to changes in parameter values for both alternans mechanisms.

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MS81

Mathematical Modeling of Sex-Specific Mechanisms in Atrial Arrhythmogenesis: A Reduced-Order Approach to Ca2+ Dynamics

Sex-related differences are observed in the incidence, presentation, mechanisms, and treatment response of atrial fibrillation (AF), the most common cardiac arrhythmia. However, the underlying biological mechanisms remain poorly understood, partly due to underrepresentation of females in experimental and clinical studies. Ca2+ handling remodeling is associated with AF pathophysiology, showing distinct characteristics in male versus female human atrial myocytes. Recently, we linked an increased propensity for Ca2+-driven arrhythmic events in female cardiomyocytes to increased RYR2 phosphorylation and the absence of L-Type Ca2+ current reduction. Here, we explore how these sex-specific differences affect tissue-level function and arrhythmogenesis. To do so, we developed reduced-order models that capture sex- and AF-dependent spontaneous Ca2+ release (SCR) behaviors, transforming our spatially detailed Ca2+ handling models into a non-spatial stochastic model to enable efficient tissue-level simulations. Our simulations indicate that female atrial tissue exhibits greater SCR-triggered delayed afterdepolarization (DAD) susceptibility than male tissue, influenced by sex-specific electrical properties and tissue-level remodeling like fibrosis and cell-cell coupling variations. This study provides insights into how sex-specific molecular, structural, and tissue factors drive Ca2+-related arrhythmogenic mechanisms in human atria, informing the development of sex-specific AF therapies.

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MS82

Heteroclinic Cycles in Pluridimensions

Robust heteroclinic cycles are sequences of equilibria along with trajectories that connect them in a cyclic manner. We investigate a class of robust heteroclinic cycles that does not satisfy the usual condition that all connections between equilibria lie in subspaces of equal dimension. We refer to these as robust heteroclinic cycles in pluridimensions. With a few reasonable assumptions, we show that such cycles require a state space of at least four dimensions and, in any dimension, a minimum of four equilibria in the cycle. We also show that there are four distinct examples of robust heteroclinic cycles in pluridimensions between four equilibria in four dimensions, and study their stability. This involves generalizing the usual Poincaré return map approach by allowing non-square transition matrices. Potential applications include modelling the dynamics of evolving populations when there are transitions between equilibria corresponding to mixed populations with different numbers of species.

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MS82

The Jungle Game Dynamics

The Jungle Game is a dynamical model for cyclic competition among species. It describes a situation where the interaction among species is achieved via a food chain, where a hierarchically superior species preys on all the species below. The last species in the chain wins when competing with the top species. The model is used to predict which species would coexist in the future. The dynamics is usually described by mean-field equations in R^n_+ , or equivalently, Lotka-Volterra dynamics, with the strength of the interaction among species expressed in the coefficients of the equations. The dynamics of the Jungle Game supports a heteroclinic network whose cycles represent species that may coexist. We study the stability of the cycles calculating the stability indices of the cycles. A stable cycle indicates that the species involved are likely to coexist. We prove that for any number of species at the initial configuration of the network, it is possible for three species to coexist in the long-run interacting through a RSP game: the bottom, top and second to the top species.

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MS82

Heteroclinic Dynamics in Network Dynamical Systems with Higher-order Interactions

Interconnected real-world systems oftentimes contain non-pairwise interactions between agents referred to as higher order interactions. Countless works in recent years have highlighted how this structural feature crucially shapes the collective behavior. We analyse whether heteroclinic structures can arise in network dynamics with higher-order interactions. In particular, we investigate under which conditions two well-known heteroclinic constructions can be realized in a corresponding network dynamical system. We find that commonly analysed model equations such as network dynamics on undirected hypergraphs induce homogeneity in the equations of motion which give rise to obstructions to the design of heteroclinic structures in phase space. By contrast, directed hypergraphs break the homogeneity and lead to vector fields that support heteroclinic structures.

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MS83

CBO Algorithm and Its Application to Dynamical Systems Theory

In this talk, we study a discrete Momentum Consensus-based optimization algorithm (Momentum-CBO) which corresponds to a second-order generalization of the discrete first-order CBO. The proposed algorithm can be understood as the modification of ADAM-CBO, replacing the normalization term by unity. For the proposed Momentum-CBO, we provide a sufficient framework which guarantees the convergence of algorithm toward a global minimum of the objective function. Moreover, we present several experimental results showing that Momentum-CBO has an improved success rate of finding the global minimum compared to vanilla-CBO and show the stability of Momentum-CBO under different initialization schemes. We also show that Momentum-CBO can be used as the alternative of ADAM-CBO which does not have a proper convergence analysis. Finally, we give an application of Momentum-CBO for Lyapunov function approximation using symbolic regression techniques. This is a joint work with Gyuyoung Hwang (IBS) and Sungyoon Kim(Stanford Univ.)

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MS83

Uniform-in-Time Mean Field Limit for Consensus-Based Optimization (cbo)

Consensus-Based Optimization (CBO) algorithms are a recent family of particle methods for solving complex nonconvex optimization problems. In many application settings, the objective function is not available in closed form. Additionally, derivatives may not be available, or very costly to obtain. CBO uses the Laplace principle to circumvent the use of gradients and is well-suited for black-box objectives. Most of the available analysis for this recent family of algorithms studies the corresponding mean-field descriptions of the distribution of particles. Convergence analysis with explicit rates is especially of interest in assessing algorithm performance and has mostly been done on the level of the mean-field PDEs. However, all results currently in the literature connecting the discrete particle system to the mean-field regime are restricted to finite time domains. In this talk, we present recent advances regarding the CBO algorithm and its variants and discuss uniform-in-time mean field limits. We touch on both first and second-order models. Second-order versions have numerical advantages in terms of convergence and provide a conceptual bridge to Particle Swarm Optimization (PSO), one of the most widely used particle-based optimization methods.

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MS83

Consensus-Based Bi-Level Optimization and its Application to Robust Federated Learning

Bi-level optimization problems, where one seeks the global minimizer of an upper-level objective over the globally optimal solution set of a lower-level objective, arise in various applications across science, engineering, and machine learning. In this talk, I will introduce Consensus-Based Bi-level Optimization (CB^2O), a multi-particle, derivative-free method for solving bi-level optimization problems with potentially nonconvex objectives. CB^2O leverages a quantile-based particle selection on the lower-level objective and a Laplace principle-type approximation for the upper-level objective, ensuring intrinsic preservation of the bi-level structure over the optimization process. In the mean-field regime, we establish exponential convergence of CB^2O dynamics to the unique solution under suitable hyperparameter choices. I will then present CB^2Os application to robust federated learning against adversarial attacks, where the training is formulated as a bi-level optimization problem. I will provide a global convergence analysis under adversarial settings, demonstrating its provable robustness against a variety of attacks. Empirically, I will show CB^2Os effectiveness in defending against label-flipping attacks in decentralized federated learning. This talk is based on joint work with Jos A. Carrillo, Nicols Garca Trillos, Aditya Kumar Akash, Konstantin Riedl, and Yuhua Zhu.

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MS84

Data-Driven Model Reduction of Fluid Flows Via Spectral Submanifolds

We present a rigorous method of model-order reduction for a class of canonical shear flows, particularly plane Couette flow and pipe flow. An extended turbulent state can coexist with the stable laminar one in these flows. The boundary between the basins of attraction is the stable manifold of distinguished coherent solutions called edge states. We show that a low-dimensional submanifold of the basin boundary can be constructed from velocity data using the recently developed theory of spectral submanifolds (SSMs). These manifolds are the unique smoothest nonlinear continuations of nonresonant spectral subspaces of the linearized system at stationary states. We use very low-dimensional SSM-based reduced-order models to predict transitions to turbulence or laminarization for velocity fields near the basin boundary in pipe flow. For plane Couette flow, we also show that the turbulent attractor is contained in a low-dimensional inertial manifold obtained as a slow SSM of the edge state.

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MS84

Computing Chaotic Time-Averages from Few Pe-

riodic Or Non-Periodic Orbits.

Temporal averages in chaotic systems can be approximated using averages associated with a collection of appropriately chosen states. For unstable periodic orbits, this connection is formalized by periodic orbit theory. Here, we describe an alternative, data-driven approach that allows for an accurate approximation of temporal averages using a collection of arbitrary segments of solutions of the governing equations embedded within the chaotic set. We show that, for a broad class of integrable observables, this approach outperforms the periodic orbit theory, achieving better accuracy while requiring far fewer states, which is paramount for high-dimensional chaotic systems. We gratefully acknowledge financial support from the National Science Foundation under Grant No. 2032657.

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MS84

Operator Inference for Systems with Translation Invariance

We consider data-driven reduced-order models of partial differential equations with translation invariance. Translation-invariant systems typically admit traveling solutions, and the main idea of our approach is to constrain the reduced-order model so that it has the same symmetry as the original partial differential equation. Existing methods for operator inference allow one to approximate a reduced-order model directly from data, without knowledge of the full-order dynamics. Our method imposes additional constraints to ensure that the reduced-order model commutes with the shift operator, thereby preserving translation invariance. We validate our approach using the Kuramoto-Sivashinsky equation, a one-dimensional partial differential equation that exhibits traveling solutions and spatiotemporal chaos. Results indicate that our method robustly captures traveling solutions, and exhibits improved numerical stability over the standard operator inference approach.

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MS84

Scale-resolving Simulations of Turbulent Flows with Coherent Structures: Toward Cut-off Dependent Data-driven Closure Modeling

There is a strong need within both industry and academia to reduce the computational cost of scale resolving simulations (SRS) which can be a million or more times more expensive than comparable Reynolds Averaged NavierStokes (RANS) simulations. A powerful framework for accomplishing this is the Partially Averaged NaverStokes (PANS) approach. When employing PANS the goal is to only resolve coherent structures and model stochastic turbulence. For such modelling to be successful it is necessary to both determine the right cut-off scale and use a suitably capable sub-grid closure model. Moreover, it is important for this model to abide by the Kolmogorov hypothesis. In this presentation we will outline our approach for using data from a variety of flows to develop a scale-sensitive data-driven closure model. Specifically, we will outline how we establish the cut-off scale, how we train a neural network for predicting sub-grid scale stresses at a variety of scales, and discuss the optimal means of incorporating unsteady features into our network. Proof of concept results for a periodic hill will be shown.

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MS85

Mitigating Bias in Decision-Making Systems

Prediction-based decision-making systems are becoming increasingly prevalent in various domains. Previous studies have demonstrated that such systems are vulnerable to runaway feedback loops which exacerbate existing biases. The automated decisions have dynamic feedback effects on the system itself. In this talk we will show how existence of feedback loops in the machine learning-based decision-making pipeline can perpetuate and reinforce machine learning biases and, by leveraging on optimal transport, we propose a fairness-promoting strategy to counteract undesired effects.

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MS85

Network Dynamics in Consumer Selection of Providers Through Online Reviews

Information spread over online review systems significantly impacts opinions and choices of people. In this study, we examine consumers' decision-making process in selecting providers based on a combination of providers' online reviews and accessibility. We propose a network-based dynamical system, in which consumers switch between providers based on online reviews, as the online review system is continuously updated with new feedbacks from the consumers. Our model is applied to various network structures, capturing both providers accessibility and the relationship between network topology and online review dynamics. Using networks of different sizes, we consistently find that online reviews have an important role in providers' success. In particular, the satisfaction of the consumers reflected in online reviews, together with the market share, influences consumer fluxes between providers and the overall quality of service experienced by consumers.

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MS85

Resilient and Pervasive Dynamics of Psychopathological Human Behaviors in the Symptoms Graphs

The modeling of human behavior considering psychopathological patterns has been recently tackled by employing a network approach based on the construction of the symptoms graph, which describes the causal relationships among the pathological signs [1]. In our study, we initially introduced the time dependence into the above graph, thus obtaining a dynamical system where the variables represent the symptoms activation levels of a mental disorder, and the equations formulation is grounded on the adjacency matrix of the symptoms graph [2]. In the second phase, to make the model more realistic, we extended it to include nonlinearities, such as a hysteretic term recognized as common in many symptoms graphs [3]. In this talk, we discuss the mathematical foundations of hysteresis, provide a formal definition, and prove some properties. After translating them to describe pathological resilient and threshold human behaviors, we find conditions under which the effects of such mechanisms, arising initially on a few nodes, can spread over the entire network. [1] Borsboom, D. (2017), A network theory of mental disorders. World Psychiatry, 16: 5-13. [2] Caporossi I., Vitanza E., Mocenni C., A nonlinear dynamic model of the symptoms graph, Conference on Complex Systems CCS2024, Exeter, September 2 6 2024. [3] Cramer A.O.J., The glue of (ab)normal mental life: networks of interacting thoughts, feelings and behaviors. Doctoral dissertation, University of Amsterdam, 2013.

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MS85

A Data-Driven Approach to Modeling Complex Traffic Systems Focusing on Human Driving Behavior

In this talk, we present a data-driven framework for modeling complex systems, with a primary focus on traffic dynamics and human driving behavior. Traditional traffic models often rely on assumptions about interactions among traffic entities, which can limit adaptability. Our framework eliminates these assumptions, employing a two-step methodology: first, we utilize information-theoretic toolsspecifically conditional transfer entropyto identify interaction directions and candidate variables; second, we apply system identification techniques like Sparse Identification of Nonlinear Dynamics (SINDy) to uncover functional relationships. Validation with synthetic data from two distinct traffic models, both subject to measurement noise, demonstrates the frameworks robustness. Analysis of real-world data reveals that drivers are responsive to both front and rear vehicles, with amplified responses to the vehicle in front during traffic jams. This framework provides an assumption-free approach to model traffic dynamics and offers valuable insights into human behavior, with broad applicability to other complex systems where understanding human interactions is crucial.

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MS86

Accelerating EMT Simulations

As the levels of power electronics-interfaced renewables such as photovoltaics (PV) and wind have risen, new operational risks caused by the dynamics of those inverter-based resources (IBRs) are also rising. Various grid events have shown that the impact of IBRs on grid stability will rise along with the increase of renewables, but the impacts of IBRs on grid stability are not fully captured by current phasor-domain dynamic simulation tools. IBRs can be controlled to mitigate those destabilizing interactions, but phasor-domain tools often cannot capture that. The existing electromagnetic transient (EMT) simulation tools can simulate detailed IBR controls, but for large power systems with many buses and IBRs, slow simulation speeds severely impede the ability to study dynamic events. Paralleling simulations using high-performance computing (HPC) can help address this, but todays EMT tools are not HPC-compatible, and parallelization of dynamic simulation solvers is not trivial because each region is coupled and can dynamically affect the others. Thus, dynamic simulation of grids with large numbers of buses and IBRs potentially poses a barrier to the ongoing energy transition. This presentation will discuss NRELs Python-based, open-source, HPC-compatible EMT simulator, ParaEMT, which is designed to accelerate the simulation of large, high-IBR power systems. It will also discuss hybrid simulation of ParaEMT with GridPACK, an open-source phasor-domain simulator.

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MS86

Adaptive Vector Valued Rational Approximations with Stable Poles

We present smiAAA, an extension of the Adaptive-Antoulas-Anderson (AAA) algorithm [Y. Nakatsukasa, O. S‘ete, and L. Trefethen, The AAA algorithm for rational approximation] to multi-input (vector valued) rational approximations with a common set of stable poles. We demonstrate the strengths of this approach compared to the stability enforcement in the FastAAA algorithm [A. Hochman, FastAAA: A fast rational-function fitter]. Results using the smiAAA algorithm are compared with the Vector Fitting algorithm [B. Gustavsen and A. Semlyen, Rational approximation of frequency domain responses by vector fitting] commonly used in EMT simulation and the more recently published RKFIT algorithm [M. Berljafa and S. Gttel, The RKFIT algorithm for nonlinear rational approximation]. Vector Fitting and RKFIT both require the user to input the number of poles to use in the approximations. If the final approximation is not accurate enough, the user must re-start Vector Fitting or RKFIT with a larger number of poles and/or a new starting location for the poles. In contrast, the smiAAA algorithm is designed to allow the user to simply input the desired accuracy of the approximations, and the necessary number of poles is detected automatically. This permits users to produce approximations of a desired accuracy with no knowledge about the underlying order of the system being approximated, preventing the algorithm from ever needing to be rerun.

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MS86

Hardware in the Loop Using Electromagnetic Transient Simulation

Digital real time simulators have the capability to run electromagnetic transient simulations in real time. This capability allows users to leverage the hardware-software combination to evaluate controller performance, protection device performance, and power device performance. This has helped many field deployment projects to be successful and be cost-effective. In this talk, we will present current state-of-art, and future of real time electromagnetic transient simulation and its impacts on field deployment.

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MS86

The Future of Electromagnetic Transient Simulation

Electromagnetic transient (EMT) simulation enables detailed modeling of the modern power grid, offering highly accurate system-level analysis. The North American Electric Reliability Corporation (NERC) has identified EMT simulations as essential for planning a reliable power grid with substantial penetration of power electronic inverters. EMT simulations of power grids involve the numerical solution of large differential-algebraic equations, which are often stiff and include delays and nonlinear dynamics. The computational burden quickly becomes impractical to simulate using the current practices as the network size and complexity due to power electronic converters increases. This talk will first review companion circuit-based method for modeling such power systems currently used by most professional simulators and then examine the challenges that limit simulation speed and scalability. We will then discuss various approaches to overcoming these challenges, including network partitioning, hybrid EMT-TSA simulation, frequency-dependent network equivalents, model order reduction, and sparse matrix techniques, in addition to the parallel simulation using the current EMT tools.

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MS87

Sparsity of Fourier Mass in Batchelors Law for Passive Scalar Turbulence

Batchelors law in passive scalar turbulence is a prediction of power spectral density for solutions to passive scalar advection in an incompressible, chaotic vector field with diffusivity and source.It is toy model of small-scale formation in more complicated systems such as hydrodynamic turbulence, mimicking the vortex-stretching mechanism believed to be at the heart of the energy cascade in hydrodynamics. In a previous work with Bedrossian and Punshon-Smith we established a cumulative version of Batchelors law for passive scalars advected by a broad class of fluid motions including that of solutions to the stochastic Navier-Stokes equation on a periodic box. In that result, it was necessary to sum over wavenumbers $\leq N$ for N large. The present paper addresses to what extent the distribution of fourier mass of a passive scalar is "evenly distributed' across frequency space. We obtain, via toy models, evidence that this distribution is sparse in that many wavenumbers have far less mass than Batchelors original predictions.Project joint with Manh Huyn Khang (Georgia Tech).

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MS87

Learning Enhanced Ensemble Filters

The filtering distribution in hidden Markov models evolves according to the law of a mean-field model in state-observation space. The ensemble Kalman filter (EnKF) approximates this mean-field model with an ensemble of interacting particles, employing a Gaussian ansatz for the joint distribution of the state and observation at each observation time. These methods are robust, but the Gaussian ansatz limits accuracy. This shortcoming is addressed by approximating the mean field evolution using a novel form of neural operator taking probability distributions as input: Measure Neural Mappings (MNM). A MNM is used to design the MNM-enhanced Ensemble Filter (MNMEF), defined in both the mean field limit and for interacting ensemble particle approximations. The ensemble approach uses empirical measures as input to the MNM and is implemented using the set transformer, which is invariant to ensemble permutation and allows different ensemble sizes. The derivation of methods from a mean-field formulation allows a single parameterization of the algorithm to be deployed at different ensemble sizes. In practice fine-tuning of a small number of parameters, for specific ensemble sizes, further enhances the accuracy of the scheme. The promise of the approach is demonstrated by establishing it as state-of-the-art, with respect to root-mean-square error, in filtering the Lorenz '96 and Kuramoto–Sivashinsky models.

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MS87

Emergence of Quasi-stationary Families of Almost-invariant Sets in Convective Fluids (Including the Atmosphere)

Diagnosing the emergence of persistent structures in turbulent nonlinear flows is important for many scientific and engineering applications. Macroscopic features of dynamical systems such as almost-invariant sets and coherent sets provide crucial high-level information on how the dynamics organises phase space. I will introduce a method to identify *time-parameterised families of almost-invariant sets* in time-dependent dynamical systems, as well as the families' *emergence and disappearance*. In contrast to coherent sets, which may freely move about in phase space over time, our technique focuses on families of metastable sets that are *quasi-stationary in space*. Our straightforward approach extends successful transfer operator methods for almost-invariant sets to time-dependent dynamics and utilises the Ulam scheme for the generator of the transfer operator on a time-expanded domain. The new methodology is illustrated with turbulent convective Rayleigh–Benard flow to identify the formation and dissipation of turbulent superstructures, and with atmospheric velocity data to diagnose the onset and decay of atmospheric blocking events, and to track the spatial extent of the block.

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MS87

Tensor Network Approximation of Transfer and Koopman Operators

A key structural property of Koopman operators of dynamical systems is that they are multiplicative on spaces of observables with a product structure. This property implies, e.g., that the point spectrum is an abelian group and that the corresponding eigenfunctions also form a group under pointwise function multiplication. Computational approximation techniques for Koopman operators typically do not preserve multiplicativity in a strict sense, yet one might expect that for approximations that are sufficiently "close" to the original operator products of eigenvalues and eigenfunctions should be useful for building models for the evolution of observables. Using this as a working hypothesis, in this talk we present a scheme for approximating Koopman and transfer operators that is based on a lift to a Fock space where regularized Koopman operators are multiplicative with respect to the tensor product. This Fock space is generated by a reproducing kernel Hilbert space of observables built such that it has the structure of a coalgebra with respect to the tensor product, and the structure of a Banach algebra with respect to the pointwise product of functions. The resulting approximation scheme can be cast in the form of a tree tensor network allowing for efficient computation in high-dimensional spaces generated multiplicatively from a modest number of approximate Koopman eigenfunctions. We illustrate this approach with applications to measure-preserving ergodic flows on tori.

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MS88

Desynchronization of Temporal Solitons in Kerr Cavities with Pulsed Injection

In this study we investigate the bifurcation mechanisms leading to desynchronization between the soliton repetition frequency and the frequency of external pulsed injection in a Kerr cavity. To investigate the case where the pulse repetition period is close to the cavity round-trip time the Lugiato-Lefever equation is used. Our results suggest that desynchronization typically occurs through an Andronov-Hopf bifurcation. Besides, we propose a simple and intuitive criterion for this bifurcation to occur. Additionally, we consider the more general scenario in which the pulse repetition period is close to the rational fraction M/N of the round-trip time modeled using the neutral delay differential equation. It is demonstrated that in this case the solitons also can exist, provided that the injection pulses are of a higher amplitude, which is directly proportional to the number M. Furthermore, we show that the synchronization range of the solitons is also proportional to the number M.

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MS88

Origin and Stability of Dissipative Solitons in Nonlinear cavities: Front Locking in Tristable Configurations

Following a pattern forming system approach, I will present a general overview on the formation and stability of dissipative localized structures in optical cavities affected by different nonlinear interaction terms. To do so, I will apply principles of dynamical systems and bifurcation theory. In particular, I will describe the formation and modification of these states in tristable configurations involving the coexistence of two homogeneous states and a Turing pattern. These results may prove essential to understanding the features and stability of a large variety of frequency combs associated with the previous localized patterns. They can be also used to unveil the bifurcation structure of high dimensional states such as dissipative light bullets.

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MS88

Existence and Stability of Oscillon Solutions for the Klein-Gordon System

This talk will focus on the Klein-Gordon system. We use variational methods to prove existence of bell-shaped oscillon solutions and provide explicit criteria for their spectral stability.

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MS89

Making Sense of the Paleoclimatic Records: A Dynamical Systems Approach

Past climate is known from indirect proxy records, mainly in form of sedimentation chronologies. The past few million years of glacial cycles (Pleistocene period) are recorded in the isotopic composition of deep sea sediments of microorganisms (foraminifera) calcium carbonate shells. The temporal resolution is millennia, while ice-core records of the past few glacial cycles show climate variability on decadal time scales and for our present climate period even annual scale. The records represent spatially integrated climate variables, with several sources of uncertainties. In the talk, I will present a brief overview of the analysis of these time series and the climate dynamics, which can be inferred from the records.

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MS89

Data-Driven Deterministic and Stochastic Subgrid-Scale Parameterization for Atmosphere and Ocean Models: A Pattern-Based Approach

Data-driven deterministic and stochastic subgrid modeling schemes for atmosphere and ocean models are discussed. Pairs of patterns in the space of resolved variables (or functions of these) and in the space of the subgrid forcing are identified and linked in a predictive manner. On top of this deterministic part of the subgrid scheme the subgrid patterns may be forced stochastically. Both the deterministic and the stochastic scheme can be constrained by physically motivated conservation laws, such as energy conservation but enstrophy dissipation. The method can also be extended by combining it with a clustering algorithm to arrive at a set of local subgrid models. The schemes are machine-learning-style but not based on deep learning. Unlike black-box approaches such as neural networks the present methodology still allows to understand and interpret the subgrid model. The subgrid modeling schemes are explored in the Lorenz 1996 model and then implemented in a quasigeostrophic three-level atmospheric model. The atmospheric model at a horizontal resolution of T30 is regarded as the reference against which coarser-resolution versions at T21 and T15, equiped with the subgrid modeling schemes, are compared. In long-term simulations, the novel subgrid schemes greatly improve on a standard hyperviscosity scheme as evidenced by the mean state, the variability pattern as well as kinetic energy and spectra. They also show marked skill improvements in an ensemble prediction setting.

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MS90

Higher-Order Phase Interactions: Symmetries, Chimeras, Heteroclinic Dynamics, and Beyond

Nonpairwise phase interactions not only arise naturally through phase reductions but also shape the network synchronization dynamics. Specific higher-order interactions give rise to symmetries that allow to analyze heteroclinic dynamics involving chimera-type synchrony patterns. We discuss how these perturb when more generic phase interactions are introduced that break these additional symmetries. Our approach combines computing an approximation of the dynamics of relative equilibria subject to forced symmetry breaking and numerical continuation of the emergent solutions.

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MS90

The Emergence of Higher-Order Interactions in Populations of Phase Oscillators

In recent years there has been a growing interest in the effect of higher-order interactions on ensembles of coupled oscillators. In order to have tractable models, people usually consider phase oscillators, such as the Kuramoto model, subject to higher-order interactions. In this talk we describe different mechanisms that lead to the emergence of higher-order interactions in populations of phase oscillators. This analysis reveals a family of interactions that naturally appear when phase oscillators are considered. Additionally, we briefly describe the displayed dynamics.

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MS90

Hamiltonian Control to Desynchronize Kuramoto Oscillators with Higher-Order Interactions

Synchronization is a ubiquitous phenomenon in Nature mainly because of its beneficial effects on the system under consideration. There are however relevant cases where a too strong synchronization or the impossibility for the system to recover its natural state can lead to undesirable behaviors; there is thus a strong need to develop suitable control methods allowing to reduce synchronization. Systems with higher-order interactions were recently proved to be relevant in modeling many real systems. Scholars revealed that the local stability of the full synchronization is more robust in this context [Zhang et. al. 2024]. We develop a feedback-pinning control method to desynchronize a Higher-order Kuramoto Model inspired by [Gjata et. al. 2017] by developping a natural higher-order generalization of the embedding Hamiltonian system proposed in [Witthaut, Timme 2014]. Our numerical results clearly confirm that the obtained control method is effective. The pairwise control strategy results to be successful in some cases, we however show that the improved control is necessary when higher-order interactions are too strong in comparison with pairwise ones. Moreover the control acts efficiently even by reducing the number of pinned nodes. Our work open new perspectives in understanding and controlling higher-order systems. Further works as optimal pinning subset search and invasiveness reduction of the control are interesting future research lines

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MS90

Pinning Control of Synchronization Patterns in Systems with Higher-Order Interactions

Understanding and controlling the mechanisms behind synchronization phenomena is of paramount importance in nonlinear science. In particular, chimera states, patterns in which order and disorder coexist simultaneously, continue to puzzle scholars, due to their elusive nature. Recently, it has been shown that higher-order interactions greatly promote the onset of chimera states, which are easier to found and more resilient when the system units interact in group. In this work, we show that the higher-order framework is fertile not only for the emergence of chimera states, but also for their control. Via pinning control, a technique consisting in applying a forcing to a subset of the nodes, we are able to trigger the emergence of chimera states with only a small fraction of controlled nodes, at striking contrast with the case without higher-order interactions. We show that our setting is robust for different higher-order topologies and types of pinning control and, finally, we give a heuristic interpretation of the results via phase reduction theory. Our numerical and theoretical results provide further understanding on how higher-order interactions shape nonlinear dynamics.

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MS91

Applications of Invariant Tori Near the Lunar Gateway in the Sun-Earth-Moon System

With Artemis, Gateway, and other planned spacecraft missions in cislunar space, mission designers need robust tools to parse the chaotic dynamical environment, analyze realistic trajectories, and produce robust mission architectures. Invariant tori found in dynamical models of cislunar space are the building blocks of these complex mission architectures. In this talk we will focus on applications to spacecraft missions associated with Gateway. We will begin by discussing the planned orbit of Gateway in the Earth-Moon Circular Restricted 3-Body Problem, as well as periodic orbits and quasi-periodic orbits that exist in its vicinity. We will then analyze the effect of the Sun, the eccentricity of the Earth-Moon orbit, and other significant perturbing influences on these solutions. We will also discuss the processes to transition these solutions into the ephemeris model. Beyond just the invariant tori related to the planned mission architecture of Gateway, it is also of interest to consider analysis related to formation flying around Gateway and transfers between orbits. So, we will present methods to design trajectories for these specific mission applications in models with different levels of fidelity. The high-level approach of these methods is often similar, but the specific implementations can be vastly different as the corresponding invariant tori often have different dimensions. We will finally discuss transitioning these mission designs into the ephemeris model.

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MS91

Leveraging Dynamical Systems Theory for Space Mission Orbit Design: Insights from the Space Weather Follow-On Mission

In this talk, we will explore how dynamical systems theory can be applied to the design of mission orbit trajectories. Using the Space Weather Follow-On L1 mission as an example, we will highlight how to utilize dynamical system principles to design and optimize the transfer trajectories and develop an efficient station-keeping strategy. We will also discuss how these techniques have been integrated to account for the specific mission requirements, demonstrating the practical advantages of this approach in real-world mission planning.

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MS91

The Dynamics in the Vicinity of Earth-Moon L2 in the Hill Restricted Four-Body Problem

The Hill restricted four-body problem (HR4BP) is a time-periodic generalization of the circular restricted three-body problem (CR3BP) that has demonstrated its utility for understanding particle motion in the Sun-Earth-Moon system. This work studies the motion in an extended neighborhood of Earth-Moon L2 in the HR4BP. In the HR4BP, the L2 equilibrium point is replaced by a periodic orbit of type center center saddle. Emanating from each center direction is a one-parameter family of two-dimensional tori. Our analysis begins by leveraging a flow map parameterization (FMP) method to rapidly trace out these families and their associated bundles. We identify several (broken) bifurcations, allowing us to compute orbits that dont have a clear analog in the CR3BP. Many of the computed tori are partially elliptic. Emanating from the bundles of these orbits are families of three-dimensional tori. We utilize the FMP algorithm to compute these families, providing a complete picture of the center manifold around Earth-Moon L2 in the HR4BP. This significantly extends previous work that was limited by the convergence restrictions of normal form methods [Peterson et al, The Vicinity of Earth-Moon L1 And L2 in the Hill Restricted 4-Body Problem] or the computational inefficiency of traditional flow map methods [Henry et al, Quasi-periodic Orbits around Earth-Moon L1 and L2 in the Hill Restricted Four-body

Problem] when studying this region.

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MS91

Toward Computer-Assisted Proofs of the Lunar Gateway's Orbit in Perturbed Models

The next-generation Lunar Gateway space station will exploit a 9:2 near rectilinear halo orbit (NRHO) about Earth-Moon L2. The majority of the literature is based on the Earth-Moon CR3BP and, in an effort to understand the problem in a more realistic setting, we consider a periodic forcing on the system. Subharmonic Melnikov (SM) theory predicts a certain number of 9:2 NRHOs persist into the perturbed system; however, due to the order of the resonance and orbit symmetry, using double precision we can compute a one-parameter family of periodic orbits in the perturbed problem. Have we discovered a degeneracy wherein SM ceases to properly predict periodicity? Or, is this something more subtle? In this talk, we show that there is a simple relationship between the resonance order, the symmetries of an unperturbed orbit, and the lowest order of the SM function having simple zeros. Consequently, the order of the first non-zero SM function is beyond double precision floating point accuracy. We present a number of pen-and-paper results in the Elliptic R3BP, followed by computer-assisted methods for the 9:2 NRHO and other resonant periodic orbits.

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MS92

Complementary Roles of Striatal D2-MSNs and D1-MSNs in Cognitive Tasks a Computational Approach

Neuronal circuits in the striatum have been often studied in the context of movement and skill learning. However, they also play a key role in executive functions, for example, in interval timing - an elementary cognitive task that requires participants to estimate an interval of several seconds by making a motor response. Recent experimental data from mice striatum show that disrupting medium spiny neurons expressing D1-type dopamine receptors (D1-MSNs) or D2-type dopamine receptors (D2-MSNs) led to response time increases. We have recently constructed a drift-diffusion model (DDM) that captures the statistics of mice behavioral data in interval timing. We propose here a data-driven mean-field model for MSN activity in interval timing, then analyze it and integrate it with our earlier low-parameter DDM to advance a computational framework for striatal executive function.

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MS92

Heterogeneity in Normalization and Attentional Modulation in a Circuit Model

The size of a neurons receptive field increases along the visual hierarchy. Neurons in higher-order visual areas integrate information through a canonical mechanism called normalization, where neurons respond sub-linearly to multiple stimuli in the receptive field. Neurons in visual cortex exhibit highly heterogeneous degrees of normalization. Interestingly, it has been demonstrated that the heterogeneity in normalization is strongly associated with the heterogeneity in attentional modulation in firing rates. However, the circuit mechanism underlying such heterogeneity is unclear. In this work, we adopt a two-layer spiking neuron circuit model, modeling V1 and V4 areas, to capture the effects of normalization and attentional modulation on both trial-average and trial-variable responses of a neural population. We find that the normalization index of each neuron is highly correlated with the magnitude of the inhibitory current it receives. In addition, the pairwise correlation between two neurons is related to their normalization indexes, consistent with a recent experimental finding. Further, our modeled attention captures the attention-mediated changes in firing rates, and improves the communication from the attended V1 location to V4 neurons. Together, our model captures several experimental findings on normalization and attentional modulation in visual cortex, and we identify inhibition to be the main determinant of the heterogeneity in these modulations.

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MS92

Efficient Computational Models of Cortical Circuits Via Coarse-Grained Interactions

Biologically realistic models of cortical circuits are challenging to build and to simulate due to the large numbers of neurons, their complex interactions, and the many unknown physiological parameters. Reduced, or coarse-grained, models are more tractable, but the degree to which they can be expected to capture the dynamics of biologically detailed spiking models is not well understood. In this talk, I will describe a coarse-graining strategy inspired by ideas from nonequilibrium statistical mechanics that aims to balance biological realism and computational efficiency. Using the primate primary visual cortex as an example, I will show that our strategy can faithfully reproduce the response of cortical circuits to external stimuli.

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MS92

Dynamics of Sensory Integration of Olfactory and Mechanosensory Input Within the Insect Antennal Lobe

Air turbulence ensures that in a natural environment insects tend to encounter odor stimuli in a pulsatile fashion. The frequency and duration of odor pulses varies with distance from the source, and hence successful mid-flight odor tracking requires resolution of spatiotemporal pulse dynamics. This requires both olfactory and mechanosensory input (from wind speed), a form of sensory integration observed within the antennal lobe (AL). In this work, we employ a model of the moth AL to study the effect of mechanosensory input on AL responses to pulsatile stimuli; in particular, we examine the ability of model neurons to encode the temporal length of a stimulus pulse versus resolving a train of brief stimulus pulses. We find that AL glomeruli receiving olfactory input are adept at encoding temporal length but less effective at tracking the temporal dynamics of a pulse train, while glomeruli receiving mechanosensory input but little olfactory input are the opposite. We speculate a possible functional division of labor within the AL, wherein, for a particular odor, glomeruli receiving strong olfactory input exhibit prolonged spiking responses that facilitate detailed discrimination of odor features, while glomeruli receiving mechanosensory input (but little olfactory input) serve to resolve the temporal dynamics of brief, pulsatile odor encounters.

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MS93

The Dependency Diagram: A New Method of Understanding Interdependence in Multivariate Distributions

Detecting, quantifying, and understanding the interdependencies within a complex system is one of the most fundamental goals of science. Information theory provides a natural platform for studying the statistical underpinnings of any system. Here, we continue a recent trend of information theoretic decompositions focused on how information is stored in dependencies rather than the variables themselves. Our decomposition can be seen as dual to the classic I-diagram, but from the vantage of dependencies rather than subset of variables. We close be demonstrating this decomposition on a variety of standard discrete distributions and discussing future directions.

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MS94

The Observed Dynamics of Mechanical Ventilation and Ventilator-Induced Lung Injury

Mechanical ventilation is a lifesaving intervention for patients who cannot breathe on their own but it can cause ventilator-induced lung injury (VILI) and worse outcomes. VILI is known to be driven by overdistension (volutrauma), cyclic collapse/reopening of distal airspaces (atelectrauma), and inflammation (biotrauma). In practice the dynamics of the lung-ventilator system, and the resulting VILI, are more complex and depend on patient state, underlying lung injury, care processes, and ventilator settings. The causative mechanisms operate on length scales form sub-micron (e.g. lung cell injury), through meters (the whole patient) and dynamically interact with each other to define the VILI response. The temporal evolution of the system is driven by intra-breath (sub-second) mechanisms, such as atelectrauma, that are manifest in days-long trajectories through the course of the hospital stay which are steered by, e.g., alveolocapillary leak and repair. Ventilator management decisions play a key role in these patient trajectories and yield bifurcations that define outcomes: once a tipping point has been reached, it can be impossible to ventilate without causing more VILI. Experimental measurements from mechanically ventilated rodents, along with clinical ventilator and electronic medical record data, will be used to explain how interactions between lung state, ventilator settings, and multiscale dynamics define VILI trajectories and patient outcomes.

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MS94

On the Observed Dynamics of Ventilator Dyssynchrony in the Human Lung-Ventilator System

The lung-ventilator system is a complex, multiscale, heterogeneous dynamical system. We focus on ventilator dyssynchrony, a highly dynamic and heterogeneous process. Ventilator dyssynchrony (VD) is the inappropriate timing of a breath in response to respiratory muscle contraction, which causes ventilator-induced lung injury (VILI). Multiple types of VD exist and vary in frequency across patients and over time in the same patient, ranging from 4–40% of all breaths. Moreover, the intensity of each type of VD varies and alters a breath's propensity to propagate VILI. Furthermore, both the frequency and intensity of VD change in time, creating shifting clusters of mild, severe, frequent, and rare VD, which interact to cause VILI. Patient-specific factors, disease course, and time-varying physiologic states further alter the risk of VILI. The integration of these features either leads to the resolution of lung injury or patient death. The bedside physician attempts to estimate these features and then optimize interventions to promote injury resolution. The first step to simplifying VD is discretizing the space by labeling the dyssynchrony in individual breaths. We created a computational pipeline to train and validate ML models to label VD accurately. We identified individual features based on clinical expertise and trained XGBoost classifiers. We identified important VD types in 9,876 manually labeled breaths with greater than 90% sensitivity and specificity.

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MS94

Evaluating Mechanically Ventilated Patient Behavior in Comparative Contexts Toward a Control Approach

Mechanical ventilation (MV) is a necessary intervention in critical care medicine. It also presents risks of patient-dependent iatrogenic injuries such as ventilator-induced lung injury (VILI), worsening of acute respiratory distress syndrome (ARDS), and mortality. Improving and personalizing care starts with investigation of MV patient data to understand interaction of human and mechanical subsystems under data-informed clinical management. Such analysis requires studying heterogeneous patient+machine+care processes -or cyborgozooid (CZ) systems- and the longer scale dynamics that result from individual breaths occurring within clinically managed contexts. Data-informed hypothesis generation is needed to improve MV although the volume and nature of CZ observations confounds the static, outcome-based approaches used in medicine. In this talk, we present a cost-oriented evolutionary game-theoretic analysis of CZ behaviors over context-limited sets of data. We then proceed to establish joint state+cost trajectories across contexts in low dimensions. This framework is an initial step toward hypothesis generation and empirical optimization of MV patient dynamics through ML applications such as Reinforcement Learning.

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MS95

Small-Noise-Induced Metastable Transition of Periodically Perturbed Systems

This work is devoted to investigating the noise-induced rare transition of periodically driven systems. The maximum likelihood paths (MLPs) are often sought, in order to reveal the transition mechanism. We show that MLPs between metastable periodic states could persist to a small nonautonomous forcing under appropriate conditions. Furthermore, we obtain a closed-form explicit expression for approximating the transition rate change. They are obtained based on standard perturbation techniques for the Euler-Lagrange equation, the Melnikov theory, as well as a linear-theory calculation. Our methods indicate a route for a detailed understanding for the interaction between periodic forcing and noise in rather general systems.

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MS95

Averaging Principle for Slow-Fast Spdes Driven by Mixed Noises

This talk investigates a class of slow-fast stochastic partial differential equations driven by fractional Brownian motion and standard Brownian motion. Firstly, the well-posedness for such equations is established. Secondly, we provide the uniform L_p-estimation for slow variable relying on the mild stochastic sewing Lemma. Finally, we obtain the approximate solution for slow variable via averaging principle.

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MS95

Fredholm Determinant As Isomonodromic τ-Function of Higher Rank Painleve System

Painleve transcendents as nonlinear special functions are widely used in mathematical physics such as random matrices, conformal field theory etc. A fruitful way to study them is through the isomonodromic deformations of some auxiliary linear systems, and a key notion in this method is the Jimbo-Miwa-Ueno τ-function. In this talk I will outline a procedure to represent isomonodromic τ-functions of a linear system with irregular singularity as Fredholm determiant, and the simplest case of which is equivalent to Painleve VI. This talk is based on a joint work with Xinxing Tang (BIMSA) and Xiaomeng Xu (PKU).

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MS96

Conditioned Stochastic Stability of Equilibrium States on Repellers

Stochastic stability provides a framework for identifying relevant invariant measures in a dynamical system, in the sense that these measures persist under random perturbations of the dynamics. Adding noise to a system washes out any invariant repelling sets and drives all points towards an attracting region of the state space. Consequently, stochastic stability has traditionally been studied only for measures on attractors. In this talk, we introduce the notion of conditioned stochastic stability of invariant measures on repellers: we examine whether quasi-ergodic measures of absorbing Markov processesgenerated by random perturbations of the deterministic dynamics and conditioned on survival in a neighbourhood of a repellerconverge to an invariant measure in the zero-noise limit. This is joint work with Matheus Manzatto de Castro (UNSW) and Jeroen S.W. Lamb (Imperial College London).

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MS96

Moment Stability and Large Deviations for Random Dynamical Systems on Non-Compact Manifolds

Let $\{v_t : t \geq 0\}$, with values in TM, denote the linearization along trajectories of a stochastic differential equation on a Riemannian manifold M, and let $\lambda_t = t^{-1} \log \|v_t\|$ denote the associated finite time Lyapunov exponent. The rate function for large deviations of λ_t from its almost sure limit λ is related via the Grtner-Ellis theorem to the moment Lyapunov exponent $\Lambda(p) = \lim_{t\to\infty} t^{-1} \log \mathbb{E}[\|v_t\|^p]$. It is well known when M is compact that $\Lambda(p)$ has a characterization in terms of an eigenvalue problem for an associated differential operator acting on functions on the projective bundle PM. We give growth conditions which, together with the standard assumptions of hypoellipticity and controllability, ensure that the eigenvalue characterization of $\Lambda(p)$ remains valid on a suitable function space. However the characterization may fail when eigenfunctions in a larger class of functions are allowed.

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MS96

Topological Bifurcation of Attractors in Hnon Map with Bounded Noise

We consider a random dynamical system with additive bounded noise. The stationary measures of such a random system are typically non-unique and supported on compact sets. The collection of all possible random trajectories can be described at a topological level as a deterministic set-valued dynamical system, whose minimal invariant sets support stationary measures of the corresponding random system. Attractors of the set-valued system, defined in the Hausdorff metric, can change discontinuously, a topological bifurcation, as systems parameters vary. We study the topological bifurcation using a finite-dimensional boundary map, defined on the unit tangent space of the Euclidean state space, which keeps invariant the unit normal bundle of the attractors boundary. The boundary map is finite-dimensional and smooth, allowing the study of invariant manifolds using existing methods. A numerical case study on the Hnon map reveals a correspondence between topological bifurcations and bifurcations in the boundary map. This is a joint work with Jeroen Lamb and Martin Rasmussen.

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MS97

Dynamics of Quartic Solitons in Resonant Cavities

Resonant cavities consist of optical elements that aim at generating optical pulses. In particular, the ability to engineer dispersion and nonlinearity allows tailoring the type of pulses (energy, width) coming out of the cavity. This work presents results on existence and stability of single and multi-pulses for cavities where dispersion is of fourth order. Our studies are based on a mean field Lugiato-Lefever PDE model. Initial studies on what should be a more realisic model: An Ikeda-like Map, will be discussed. This work is in collaboration with Dr. Ross Parker (Research staff, Center for Communications Research, Princeton NJ) and Dr. Sabrina Hetzel (Postdoctoral fellow, Virginia Tech)

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MS97

Dynamical Reduction for Solitonic Filaments

In this talk we describe techniques for the dynamical reduction of soliton stripes in nonlinear spatio-temporal systems. The central idea is to cast reductions to accurately describe these structures with lower-dimensional models that are more easily tackled, both mathematically and computationally. In turn, the reduced models allow for an unprecedented description of the statics, stability, dynamics, and interactions of these structures.

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MS97

Dynamics of Temporal Localized Structures in Time-Delayed Micro-Cavities

We discuss the existence of a novel type of temporal localized structure in injected Kerr-Gires-Tournois interferometers. These bright pulses exist both in the normal and anomalous dispersion regimes, yet they do not correspond to the usual scenario of domain wall locking or cavity solitons formation. The new states are observed beyond the mean-field limit and out of the bistable region. Their shape is uniquely defined, with peak intensities beyond that of the upper steady state, and they are stable over a broad range of the injection field, highlighting their potential for optical frequency comb generation.

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MS97

Dynamics and Stability of Solitons in Dual-Pumped Microresonators

Multi-color solitons, generated in dual-pumped microresonators, feature components (”colors”) with a single angular group velocity and distinct angular phase velocities. These solitons produce interleaved frequency combs that can be modeled using the multi-pump Lugiato-Lefever equation (MLLE). However, MLLE solutions are generally non-stationary, offering limited insight into the comb structure and soliton stability. We derive three-wave equations describing multi-color soliton dynamics with stationary solutions. By linearizing these equations around the stationary state, we analyze soliton stability via eigenvalue spectra. A special case arises when the second pump is tuned close to a comb line of the soliton from the primary pump. Here, the second pump ”captures” the closest comb line, synchronizing the solitons colors into a single angular group and phase velocity. We refer to this phenomenon as Kerr-induced Synchronization (KIS). By plotting the eigenvalue spectrum of the MLLE that is linearized around the stationary solution, we observe that the zero eigenvalue associated with the soliton’s translational invariance becomes negative. This implies that perturbations to the soliton position damp exponentially with the photon lifetime. We analytically, numerically, and experimentally demonstrate that KIS significantly reduces the impact of intra-cavity noise on soliton repetition rates, enabling low-noise, all-optical, octave-spanning integrated frequency combs.

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MS98

Studying Stability of Shear Flows Using Sum-of-Squares Polynomial Optimization

The stability of steady states for complex dynamical systems are notoriously difficult problems, even for the seemingly simplest cases. For example, it is expected that the standard steady state shear profile for 2D Couette flow is globally stable for all Reynolds numbers, however the state-of-the-art analysis using standard energy method approaches is nearly a century old and only proves the stability for relatively low Reynolds numbers or small initial data. In recent years, a promising computational approach uses polynomial sum-of-squares optimization to learn Lyapunov functions based on low-mode projections onto an orthogonal basis of $L^2 \cap H^1$, which has inherent symmetries we can prove simplify the problem. I will present both my analytical and computational extensions on existing work in this area.

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MS98

Self-Similar Singular Solutions for the Nonlinear Schrdinger Equation and the Complex Ginzburg-Landau Equation

In 2001, Plechc and verk gave strong numerical evidence for the existence branches of backwards self-similar singular solutions to the complex Ginzburg-Landau equation. We now present a rigorous proof of these branches existence, which in particular includes the 3D cubic Schrdinger equation. Our proof follows the same strategy as Plechc and verk, which reduces the problem to proving the existence of a solution to a certain ODE with prescribed behaviour at zero and infinity. Near zero the solution is constructed using a rigorous numerical ODE solver and near infinity by carefully analysing the asymptotic expansion. These two solutions are then glued together to form the full solution.

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MS98

Polynomial Optimization Methods for Dynamics and Their Potential for Computer-Assisted Proof

Computational polynomial optimization, particularly with sum-of-squares constraints, can be used to infer many types of mathematical statements about nonlinear dynamics governed by ODEs or PDEs. These methods rely on constructing functions that satisfying suitable inequalities. A familiar example is proving stability by constructing Lyapunov functions, but similar approaches can give bounds on attractor properties or transient behavior, estimates of basins of attraction, design of optimal controls, and much more. This talk will give an overview of these methods and show some computational examples. It will also discuss the potential to make such computational results rigorous to the standard of computer-assisted proof by using interval arithmetic, rational arithmetic and/or computer algebra.

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MS98

The Lorenz System As a Gradient-Like System

We formulate, for continuous-time dynamical systems, a sufficient condition to be a gradient-like system, i.e. that all bounded trajectories approach stationary points and therefore that periodic orbits, chaotic attractors, etc do not exist. This condition is based upon the existence of an auxiliary function defined over the state space of the system, in a way analogous to a Lyapunov function for the stability of an equilibrium. For polynomial systems, Lyapunov functions can be found computationally by using sum-of-squares optimisation. We demonstrate this method by finding such an auxiliary function for the Lorenz system. We are able to show that the system is gradient-like for 0=?=12 when s?=?10 and =8/3, significantly extending previous results. The results are rigorously validated by a novel procedure: First, an approximate numerical solution is found using finite-precision floating-point sum-of-squares optimisation. We then prove that there exists an exact solution close to this using interval arithmetic.

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MS99

Learning Cell Fate Decisions Under Environmental Stress

In this talk, we study cell fate decisions in a gene regulatory network under abrupt exposure to antibiotics. In particular, we analyze bifurcations for the external drug concentration parameter. Moreover, we infer parameters to match with the single-cell data in Schultz et al. 2017 by formulating our inference as an ODE-constrained optimization problem and solve it using machine learning. Our work sheds light on how the interactions between gene regulatory networks and metabolisms influence emergent population-level dynamics. This is joint work with Ethan Levien and Daniel Schultz.

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MS99

Ovarian Aging and Oocyte Stochasticity

Several mysteries surround ovarian aging in women. What triggers menopause? What triggers the menopausal transition? Can the timing of these landmarks of aging be predicted? Can they be delayed? Why are women born with a so-called "wasteful oversupply" of eggs? In this talk, we will highlight (1) how stochasticity at the level of individual oocytes gives new insight into these old questions and (2) the mathematical questions which emerge from this analysis.

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MS99

Population Dynamics and Universal Statistics of Tumor-Inhabiting Bacteria

Bacterial colonization of solid tumors is widespread, but the dynamics of colonization are poorly understood. Our collaborators' experiments with DNA-barcoded bacteria in mouse tumors show that after an initial expansion period, bacterial clone sizes exhibit universal power-law statistics. These statistics are robust across experiments and collection times, and unique to bacteria grown in the tumor environment rather than in liquid culture. Combining population ecology with nonequilibrium statistical physics, we develop a dynamical model of intra-tumor bacterial growth that includes an infection bottleneck, local growth constraints, global resource competition, and environmental noise. Our simple model captures the dynamics and the statistics of the experiments, explains the uniqueness of the observations to the tumor environment, and represents an important step in quantitatively characterizing the tumor microbiome.

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MS99

Criticality in Cell Populations with An Arbitrary Mutation Rate: a Generalized Luria-Delbruck Mode

The Luria-Delbrck model is a classic model of population dynamics with random mutations, that has been used historically to prove that random mutations drive evolution. In typical scenarios, the relevant mutation rate is exceedingly small, and mutants are counted only at the final time point. Here, inspired by recent experiments on DNA repair, we study a mathematical model that is formally equivalent to the Luria-Delbrck setup, with the repair rate p playing the role of mutation rate, albeit taking on large values, of order unity per cell division. We generalize the Luria-Delbrck model for large effective mutation rate and find a surprising phase transition behavior at p=1/2, and the modified model fits well with the experiment when the probability of a successful repair process is considered.

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MS100

A Mean-field Sigmoidal Bounded Confidence Model of Opinion Dynamics

Mathematical models of opinion dynamics are an important tool to gain insight into the qualitative dynamics of the evolution of opinions or ideologies over time. The sigmoidal bounded-confidence model (SBCM) is a smooth, nonlinear model of opinion dynamics which is parameterized by a scalar γ. This parameter controls the steepness of a smooth influence function that encodes the relative weights that agents place on the opinions of other agents, and interpolates between two well-studied models of opinion dynamics. When $\gamma = 0$, this influence function exactly recovers Taylors averaging model; when $\gamma \to \infty$, the influence function converges to that of a modified Hegselmann-Krause (HK) model. However, analyzing stationary states and bifurcations in the SBCM remains a difficult challenge. We derive a continuity equation for the sigmoidal bounded-confidence model of opinion dynamics, which yields an integro-partial-differential equation. We prove the existence of unique solutions and prove some properties of the stationary states, including providing some conditions under which consensus states may be achieved.

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MS100

Constructing Twisted States on Fractals

In systems of coupled phase oscillators, twisted states arise naturally as equilibria on ring networks. As such, twisted states are minimizers of an associated S^1-valued energy functional. In this work we generalize this to the construction of analogous twisted states on fractal networks. We first define how to construct an appropriate energy form on fractal sets, and then introduce a novel geometric approach for constructing and classifying twisted states on these intricate networks. Due to the complex topology of fractals, there is a much richer collection of possible twisted states that emerge. Our method relies on the so-called harmonic extension algorithm applied to covering spaces of the fractal. We will present our results on several representative fractal examples, including the Sierpinski Gasket, the hexagasket, and the pentagasket.

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MS100

Opinion and Consensus Formation in the Presence of Polyadic Interactions

Opinions are rarely formed in isolation but rather through interactions with other individuals in society. As such, they are a product of each individual's social neighbourhood, but, at the same time, they also shape this neighbourhood. Classical models of opinion formation, such as the adaptive voter model, demonstrate how the interplay between the propagation of opinions and the adaptation of the social neighbourhood can ultimately, if the latter dominates, lead to a fragmentation of society. However, focussing exclusively on pairwise interactions, these models cannot capture forces like the striving for conformity that manifests itself, for instance, in peer pressure. Instead, to accomplish this, it is necessary to take group interactions into account, and in this talk, I will discuss their impact on opinion formation. To this end, I will present a generalisation of the adaptive voter model that involves considering the analogous processes of propagation and adaptation from the classical model on an underlying hypergraph instead of a graph. Finally, I will also discuss how the presence of very large groups may affect the overall dynamics and, in particular, stabilise the system, preventing it from fragmentation.

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MS100

Synchronization in ErdosRnyi Graphs with Kuramoto Dynamics: A Graphon Approach

Two well-known phase oscillator models, the Kuramoto and Sakaguchi-Kuramoto models, are widely used to study synchronization behavior in various applications. Recent research explores synchronization in these models on random networks. In this work, we analyze a general oscillator model on a W-random network generated from a graphon, W, and compare it to a continuum oscillator model with graphon-based interactions. Using results obtained from this comparison, coupled with a basin of attraction argument, we show that the Sakaguchi-Kuramoto model on an ErdosRnyi graph achieves frequency synchronization with high probability as $n \to \infty$, assuming a fixed edge probability $p \in (0, 1]$.

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MS101

From the Lagrange Triangle to the Figure Eight Choreography: About a Conjecture of C. Marchal

In the context of the three-body problem with equal masses, Marchal conjectured in 1999 that the most symmetric continuation class of Lagranges equilateral triangle solution, known as the P12 family of Marchal, includes the remarkable figure-eight choreography discovered by Moore in 1993 and proven to exist by Chenciner and Montgomery in 2000. In this talk, I will present a framework for verifying the existence of the P12 family as a zero-finding problem. Additionally, we will explore the relation between this verification and Marchal's conjecture. This work is a collaboration with Carlos Garca-Azpeitia, Olivier Hnot, Jean-Philippe Lessard, and Jason Mireles James.

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MS101

Exploring Exoplanetary Systems by Periodic Syzygy Orbits

In this talk, we will explore periodic syzygy orbits in the context of exoplanetary systems, building on solutions to the Three-Body Problem (TBP) first discovered by H. Poincar in 1892. These orbits describe trajectories in which the system's bodies align periodically, transitioning through distinct configurations as they orbit one another. I will discuss how these periodic syzygy orbits can be numerically computed, examine their stability properties, and present interesting case studies of specific exoplanetary configurations. This approach offers a fresh perspective on the dynamical behavior of multi-body systems, with broad implications for understanding exoplanetary motion, orbital resonances, and their potential applications in various scenarios in Celestial Mechanics. This is an ongoing project with . Jorba, M. Jorba-Cusc, and B. Nicols.

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MS101

Attributes of Specific Dynamics in the Hill Four-body Problem Considering Oblateness

Consider a restricted four-body problem with a hierarchical arrangement of the bodies: two larger bodies, a smaller one, and a fourth infinitesimal body, which is modeled as an oblate spheroid. By applying the Hill approximation and regularizing the system using the McGehee coordinate transformation, we analyze the dynamics in various motivating applications, accounting for different levels of oblateness.

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MS101

Analysis of Resonant Dynamics: The Hilda Asteroids

The Hilda group of asteroids, numbering over 6000, resides beyond the main asteroid belt, within Jupiter's orbit. These objects are known to have mean motion in a 3:2 orbital resonance with Jupiter and to describe orbits that seem to successively approach three Lagrangian points, L_3, L_4 and L_5, of the Sun-Jupiter system. In this talk, we will present an analysis of the dynamical behavior of Hilda asteroids using the Circular and Elliptical Restricted Three-Body Problems (CRTBP and ERTBP) in the planar case, focusing on the role of Jupiter's eccentricity. Our analysis starts by selecting those asteroids in the JPL database with orbital elements of the Hilda category, although focusing on those with low inclination. These asteroids are initially defined in an inertial ecliptic reference frame, and we will discuss the transformation of their coordinates into the Sun-Jupiter system for both the CRTBP and ERTBP models. This transformation is based on the instantaneous orbital elements of the Sun and Jupiter. Once the coordinates are transformed, we will present the results of our numerical analysis of periodic and quasi-periodic orbits that govern the motion of these asteroids. Quasi-periodic orbits (or invariant tori) are investigated using Poincar sections, with comparisons made between different strategies to assess their stability. Some results will be presented for both the circular and the elliptical restricted three body problems.

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MS102

Liouville Flow Importance Sampler

I will present the Liouville Flow Importance Sampler (LFIS), an innovative generative machine learning model for generating samples from unnormalized density functions. LFIS adopts a self-learning approach to learn a time-dependent velocity field that deterministically transports samples drawn from a simple initial distribution to a complex target distribution, guided by a prescribed path of annealed distributions. The training of LFIS utilizes a unique method that enforces the structure of a derived partial differential equation on neural networks modeling velocity fields, akin to Physics-Informed Neural Networks. By considering the neural velocity field as an importance sampler, a surprising result emerges: the sample weights can be quantified by accumulating the error along the trajectories driven by neural velocity fields. This discovery facilitates an unbiased and consistent estimation of statistical quantities. We demonstrate the effectiveness of LFIS through its application to a range of benchmark problems, many of which show that LFIS achieved state-of-the-art performance over other neural network-driven methods.

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MS102

Continuous Perron Frobenius Operator and Stochastic Sensitivity Analysis for Dynamical Systems

We derive local sensitivities of statistical quantities of interest with respect to model parameters in dynamical systems using the continuous Perron Frobenius operator. We extend classical adjoint-based a posteriori analysis for dynamical systems acting on states to the Liouville operator acting on probabiliity densities of the states which gives us exact mathematical formulation of sensitivity and error for a broad class of computed quantities of interest while propagating uncertainty through dynamical systems. We also derive Monte-Carlo type estimators to make these estimates computationally tractable using spatio-temporal normalizing flows. Three examples demonstrate our method. First, we use a 2D linear dynamical system with an initial multivariate Gaussian density. Then, we apply our method to the challenging task of propagating uncertainty in a double attractor system to illlustrate sensitivities in bimodal distributions. Finally, we show that our method can provide sensitivities with respect to the parameters of Neural Ordinary Differential Equations (here, in the context of classification) and we show how sensitivities change when the Neural ODE is applied to out of distribution data.

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MS102

Model Reduction for Deep Networks

It is well known that feed forward neural networks can be usefully viewed as discretizations of large systems of ODEs. At the same time, a plethora of methods have been developed to reduce the dimensionality of dynamical systems. This talk reports on a study of model reduction methods applied to deep feedforward networks.

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MS102

When Big Neural Networks Are Not Enough: Physics, Multifidelity and Kernels

Modern machine learning has shown remarkable promise in multiple applications. However, brute force use of neural networks, even when they have huge numbers of trainable parameters, can fail to provide highly accurate predictions for problems in the physical sciences. We present a collection of ideas about how enforcing physics, exploiting multifidelity knowledge and the kernel representation of neural networks can lead to significant increase in efficiency and/or accuracy. Various examples are used to illustrate the ideas.

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MS103

Network Architecture of Neural Signaling and Anatomy in C. Elegans

The connectome describes the complete set of synaptic contacts through which neurons communicate. While the architecture of the *C. elegans* connectome has been extensively characterized, much less is known about the organization of causal signaling arising from functional interactions between neurons. Understanding how effective communication pathways diverge from the underlying structure is a central question in neuroscience. Here, we analyze the modular architecture of the *C. elegans* signal propagation network and compare it to the underlying anatomical wiring. We identify a hierarchy of communities comprising 3 tiers of organization, the coarsest of which contains 6 modules. We find that signaling modules are not aligned with the modular boundaries of the anatomical network, highlighting an instance where function deviates from structure. We analyze the cellular compositions of this signaling architecture and find that its modules are enriched for specific cell types and functions, reinforcing their neurobiological relevance. Lastly, we identify a rich club of hub neurons in the signaling network, whose membership differs from the rich club detected in the anatomical network, challenging the view that structural hubs occupy positions of influence in signaling. Our results comparing the complete nanoscale connectome and the system-wide causal signal propagation atlas provide new insight into the interplay between brain structure and brain function.

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MS103

Whole-Brain Modelling at Cellular Resolution: Grounding Odes in Whole-Brain Imaging Data

Understanding how brain activity in living animals emerges from the concerted interaction of neurons is a major challenge of neuroscience. By capitalizing on the increasing availability of whole-brain imaging data, in the last decade whole-brain models have proven useful in shedding new light on the mechanisms that shape collective neural activity in mammals. The development of whole-brain imaging techniques in freely-moving animals is also advancing rapidly, with the nematode C. elegans paving the way. The limited size and experimental tractability of the C. elegans nervous system, means that the growing body of neuronal imaging data, combined with extensive characterization of the nervous system, offers a unique opportunity to understand the emergence of whole-brain dynamics, at cellular resolution. While C. elegans whole-brain imaging data has already led to important insights on low-dimensional attractors encoding whole-brain activity and its correspondence to behavioral states, the development of mechanistic whole-brain models grounded in such data poses a number of fundamental and technical challenges. Here, we tackle those difficulties by designing new interdisciplinary approaches that rely on recent theoretical and algorithmic developments from applied mathematics and deep learning. Our aim is to integrate our results into a digital twin of the C. elegans nerve ring, linking for the first time single-cell activity, connectomics, whole-brain dynamics and behavior.

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MS103

Connectome-Constrained Dynamics in a Highly Neuromodulatory Circuit: Lessons from the C. Elegans Pharynx

The pharynx, part of the C. elegans digestive system, has a small repertoire of behaviors that include both feeding via fluid intake and periodic pumping, but also emergency responses, such as shutting down digestion via pumping inhibition and fluid intake flow reversal, or spitting. These actions are orchestrated by a small number of recurrently connected neurons whose dynamics are governed by both structural and wireless connections. Here we develop a computational framework to study this interaction of connectome-constrained dynamics with additional state dependent processes such as neuromodulation. We show a degenerate solution space, and investigate necessary and sufficient constraints for collapsing to unique solutions.

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MS103

Investigating Neuronal Network Activity After Prolonged Experience

How is complex experience deconvolved and given significance in the brain? How does the brain mark certain parts of an experience as important enough to produce a stable memory and others to be pruned? Here we find that after swim-based aversive olfactory conditioning, C. elegans learn to respond to liquid environments faster than nave animals and that this memory may be stable. Preliminary evidence suggests that odor experience can bolster the stability of this motor memory. We also found that the stereotypical neural dynamics that underly motor behavior are also changed by swim experience. Interestingly, some, but not all swim motor plan information is integrated into a brand-new crawling motor plan. We hope to ask if the recently uncovered paired oscillators (Dunn et al, 2024 BioRXiv) that couple motor behaviors are affected by this swim experience integration.

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MS104

Data Driven Method to Learn The Stochastic Dynamical Systems and Its Application In Polymer Dynamics

In this talk, I will discuss how to use machine learning method to learn the stochastic problem. To begin, I will introduce the how to combine physics informed neural network(PINN) method and the sample observation data to learn the stochastic differential equation driven by Brown and Levy noise. Second, I will introduce how to use stochatic OnsagerNet to learn closure dynamical systems. We propose a general machine learning approach to construct reduced models for noisy, dissipative dynamics based on the Onsager principle for non-equilibrium systems. Then I will demonstrate our method by modelling the folding and unfolding of a long polymer chain in an external field - a classical problem in polymer rheology - though our model is suitable for the description of a wide array of complex, dissipative dynamical systems arising in scientific and technological applications.

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MS104

Critical Transition and Tipping in Brain Diseases

With the development of machine learning techniques, data-driven approaches are becoming increasingly important in real-world modeling with stochastic dynamical systems. However, in the field of neural science problems, these approaches are still in their early stages. We first review some neural inverse problems to deepen the understanding of neural dynamics in complex brain systems. Then we propose some applications to model tipping phenomena and optimal control in brain diseases. The methods include large deviation theory, optimal control, and Schrodinger Bridge.

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MS104

Learning Generalized Diffusions Using An Energetic Variational Approach

Extracting governing physical laws from computational or experimental data is crucial across various fields such as fluid dynamics and plasma physics. Many of those physical laws are dissipative due to fluid viscosity or plasma collisions. For such a dissipative physical system, we propose three distinct methods to learn the corresponding laws of the systems based on their energy-dissipation laws, assuming either continuous data (probability density) or discrete data (particles) are available. Our methods offer several key advantages, including their robustness to corrupted observations, their easy extension to more complex physical systems, and the potential to address higher-dimensional systems. We validate our approach through representative numerical examples and carefully investigate the impacts of data quantity and data property on the model discovery.

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MS105

Metastability and Quasi-Ergodic of High-Dimensional Interacting Particle Systems

I study the behavior of high-dimensional particle systems near attracting manifolds. In the large size limit, Mckean-Vlasov Theory implies that the flow of the empirical measure becomes to deterministic. I consider systems where the limiting flow operator has a smooth invariant manifold, and I determined approximate expressions for the quasi-ergodic distribution of the empirical measure near this manifold. Over timescales that are exponential in N, I prove that the occupation measure of the empirical measure converges to this distribution.

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MS105

Superlinear Multiplicative Noise Can Cause Or Prevent Explosion in SPDEs

A mild solution to an SPDE explodes in finite time if one of its values becomes infinite. Generally, solutions cannot be extended beyond this explosion time. Adding stochastic forcing to a deterministic PDE can lead to surprising behaviors. In some settings, the addition of stochastic noise can cause explosion. In other settings, the addition of stochastic forcing can prevent explosion.

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MS106

Dynamics of Mesoscopic Brain Models with Microscopic Features

We recently introduced mesoscopic brain model elements we denote as mechanistic neural mass (mNM) elements that link membrane-level mechanics, and especially membrane level bifurcations in dynamics, to the dynamics of mean-field elements (Tripathi and Gluckman 2022). Here we demonstrate tools to map other neural mass model parameters onto networks composed of such elements, how to link genetic-mutation based features to the mesoscale, and some of richer dynamics that emerge from such mechanism-linked networks.

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MS106

Noisy Delay Denoises Biochemical Oscillators

Genetic oscillations are generated by delayed transcriptional negative feedback loops, wherein repressor proteins inhibit their own synthesis after a temporal production delay. This delay is distributed because it arises from a sequence of noisy processes, including transcription, translation, folding, and translocation. Because the delay determines repression timing and therefore oscillation period, it has been commonly believed that delay noise weakens oscillatory dynamics. Here, we demonstrate that noisy delay can surprisingly denoise genetic oscillators. Specifically, moderate delay noise improves the signal-to-noise ratio and sharpens oscillation peaks, all without impacting period and amplitude. We show that this denoising phenomenon occurs in a variety of well-studied genetic oscillators and we use queueing theory to uncover the universal mechanisms that produce it.

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MS106

Oscillations in Delayed Positive Feedback Systems

Positive feedback loops exist in many biological circuits important for organismal function. In this talk, we show how temporal delay affects the dynamics of two canonical positive feedback models. To do this, we consider models of a toggle switch and a one-way switch with delay added to the feedback terms. We show that long-lasting transient oscillations exist in both models under general conditions. We discover that the duration of the transient oscillations depends strongly on the magnitude of the delay and initial conditions. We then exhibit the existence of long-lasting oscillations in specific biological examples: the Cdc2-Cyclin B/Wee1 system and a generic genetic regulatory network. Our results challenge fundamental assumptions underlying oscillatory behavior in biological systems. While generally delayed negative feedback systems are canonical in generating oscillations, we show that delayed positive feedback systems are a mechanism for generating oscillations as well.

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MS107

Data-driven Computational Methods for the Fokker-Planck Equation

The Fokker-Planck equation, which describes the time evolution of the probability density function of stochastic differential equations, is a powerful tool for modeling stochastic dynamics. However, in many applications, the equation becomes high-dimensional, posing significant challenges for numerical computation. In this talk, I will present a series of data-driven numerical methods developed to solve high-dimensional Fokker-Planck equations and compute their eigenfunctions. A key aspect of these methods is the integration of low-accuracy Monte Carlo simulations to guide optimization or artificial neural network training, enabling efficient and scalable solutions.

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MS107

Stochastic Oscillations in the KaiA/B/C Circadian Rhythm Circuit

Living systems exhibit various robust dynamics during system regulation, growth, and motility. However, how robustness emerges from stochastic components remains unclear. Towards understanding this, I develop topological theories that support robust edge currents and localization, effectively reducing the system function to a lower-dimensional subspace. I will introduce stochastic networks in molecular reaction space that model long and stable time scales, such as the circadian rhythm. Our work establishes the framework of topological invariants relevant for a broad class of emergent oscillations and dynamics in biology.

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MS107

Mathematical Foundations of Phase and Isostable Reduction for Stochastic Oscillators

Many systems in physics, chemistry, and biology exhibit oscillations with a pronounced random component. Such stochastic oscillations can emerge via different mechanisms, for example, linear dynamics of a stable focus with fluctuations, limit-cycle systems perturbed by noise, or excitable systems in which random inputs lead to a train of pulses. Despite their diverse origins, the phenomenology of random oscillations can be strikingly similar. Here, we introduce a nonlinear transformation of stochastic oscillators to a complex-valued function that greatly simplifies and unifies the mathematical description of the oscillators spontaneous activity, its response to an external time-dependent perturbation, and the correlation statistics of different oscillators that are weakly coupled. The function is the eigenfunction of the Kolmogorov backward operator with the least negative (but nonvanishing) eigenvalue.

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MS107

Oscillations in Balanced Neural Networks

We study high dimensional balanced neural networks. These are such that there are two types of neurons: excitatory and inhibitory. Any particular neuron typically receive approximately the same number of inputs from both types of neuron. Thus the mean inputs to a neuron balance, and the fluctuations about the mean drive the dynamics. We determine limiting equations for the correlation functions, and investigate parametric regimes under which these equations are oscillatory.

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MS108

Dynamics-Aware Filtering and Physical Generative ModelinginChaotic Systems

The physical measures of some chaotic systems inherently have a low-dimensional absolutely continuous conditional structure on unstable manifolds. Here we discuss numerical methods that exploit such structure for efficiently learning surrogate models and for Bayesian data assimilation in high-dimensional chaotic systems. Specifically, we develop an algorithm to learn the scores or gradient log densities associated with conditional measures on unstable manifolds. We discuss the convergence of this approximate score learning and the effect of the approximation (along finite-length orbits) on sampling from Bayesian filtering distributions. We draw a connection between our score learning algorithm and regression for learning dynamical systems. We show conditions under which learning the one-time map can reproduce statistics with respect to the underlying physical measure.

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MS108

Learning Hamiltonian and Poisson Dynamics From Time Series

Random feature maps are a computationally cheap approach for supervised learning. They can be used to learn the Hamiltonian function of a system with known Hamiltonian structure from time series data. A serendipitous side-effect of this approach is a class of symplectic splitting methods that can be employed to do to predictions with the learned dynamics. We will give some examples and discuss efficiency and scaling with dimension. When the symplectic structure is unknown, or when the system has unknown Lie-Poisson or Poisson structure, one may attempt to learn the structure and Hamiltonian simultaneously. We also discuss experiences with the latter.

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MS108

Data-Driven Reconstruction of Dynamical Systems with the Spectral Exterior Calculus

In this talk, a data-driven framework will be introduced for the reconstruction and forecasting of dynamical systems on Riemannian manifolds, utilizing spectral exterior calculus to represent vector fields. In this approach, eigenvalues and eigenfunctions of the Laplace operator on smooth functionsapproximated via the diffusion maps algorithmmare employed to build overcomplete bases, which act as generators for dynamical systems on the manifold. Through this method, vector fields are approximated as linear combinations of frame elements in L2 and Sobolev spaces, allowing data-driven vector field representations. Monte Carlo sampling is used to estimate vector fields from data points sampled on low-dimensional manifolds, such as the circle and 2-torus, providing flexibility for complex geometries. Initial-value predictions are then performed using these learned vector fields, and forecasted trajectories are compared to those of the true system, with accuracy and stability examined. Insights into the advantages and limitations of this data-driven approach for forecasting in dynamical systems will also be discussed.

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MS110

Improving DMD Analysis of Tandem Cylinder Flow Using Nonlinear Dictionaries

In this talk, we discuss the impact of using a **nonlinear** dictionary of basis functions when applying different methods of dynamic mode decomposition to a fluids-based experimental example. The experiment involves the flow interaction with two tandem cylinders positioned in a bistable configuration such that two distinct shedding frequencies are observed. These frequencies are the main focus of the analysis but more generally the experiment demonstrates that a more complete understanding of the flow is achievable with a more carefully selected dictionary. The study influenced the adaptation of Rigged DMD to nonlinear dictionaries (titled 'kRigged DMD'), for which flow features are captured more successfully.

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MS110

Rigged Dmd: Modal Koopman Decompositions for the Continuous Spectrum

Koopman operator theory provides a powerful framework for data-driven analysis of nonlinear dynamical systems. At its heart, the Koopman operator governs the evolution of observables on the state-space and allows one to construct reduced-order models, extract meaningful features of the dynamics, and more. However, there is a pressing need for algorithms that capture coherent features of dynamical systems associated with a continuous Koopman spectrum. In this talk, we show how to rigorously compute such coherent features of measure-preserving dynamical systems with continuous spectrum. Our algorithm, Rigged DMD, uses a measure-preserving Dynamic Mode Decomposition to construct carefully regularized wave-packet approximations to the generalized eigenfunctions of unitary Koopman operators in rigged Hilbert spaces. We discuss the basic convergence properties of the algorithm and illustrate with a number of examples, including the nonlinear pendulum, the Lorenz system, and a high-Reynolds number lid-driven flow in a two-dimensional cavity.

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MS110

Dynamic Mode Decomposition Variants and Extensions for Robust Data-Driven Modeling

The dynamic mode decomposition (DMD) is a data-driven reduced-order modeling technique that decomposes time-varying data sets into coherent spatiotemporal modes. This representation of the data allows for a large variety of tasks, including dimensionality reduction, future-state prediction, and system control, which has led to the methods utilization and success across many scientific disciplines. In this talk, we discuss several major developments regarding DMD and its applications. In particular, we explore two recent methodological extensions of the DMD algorithm: (1) sparse-mode DMD for generating spatially local DMD modes, and (2) mrCOSTS for decomposing multi-scale data sets. We demonstrate key insights provided by these different approaches by analyzing synthetic and real-world systems, including sea surface temperature patterns and optical waveguides. In addition to reviewing new DMD variants, we also discuss the use of time-delay embeddings in conjunction with DMD models. Recent findings suggest that time-delays can be used to not only apply DMD to partial measurement data, but also to identify chaotic behavior even in the absence of measurements that embed the true underlying system. We thus explore this phenomenon and discuss how it might inform our understanding of Takens-embeddable coordinates and time-delay DMD models.

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MS110

Analytic Edmd: The Ultimate Data-Driven Spectral Method for Equilibria?

We present a novel EDMD-type method that captures the spectrum and eigenfunctions of the Koopman operator defined on a reproducing kernel Hilbert space of analytic functions. Our approach relies on an orthogonal projection on polynomial subspaces, which is equivalent to data-driven Taylor approximation. In the case of dynamics with a hyperbolic equilibrium, the proposed method demonstrates excellent performance to capture the lattice structured Koopman spectrum, including the eigenvalues of the linearized system at the equilibrium. In particular, it remains efficient with partial state measurements or with a dataset generated far from the equilibrium. More importantly, this technique preserves and exploits the triangular structure of the operator so that it does not suffer from spectral pollution, reaching arbitrary accuracy on the spectrum with a fixed finite dimension of the approximation. This property will be demonstrated by numerical simulations and validated with theoretical error bounds.

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MS111

Unbounded Hamiltonian Simulation: Quantum Algorithm and Superconvergence

Simulation of quntum dynamics, emerging as the original motivation for quntum computers, is widely viewed as one of the most important applications of a quntum computer. Recent years have witnessed tremendous progress in developing and analyzing quntum algorithms for Hamiltonian simulation of bounded operators. However, many scientific and engineering problems require the efficient treatment of unbounded operators, which pose additional challenges, often arising from the discretization of differential operators. Such applications include molecular dynamics, electronic structure, quantum differential equations solver and quantum optimization. We will introduce some recent progresses in quantum algorithms for efficient unbounded Hamiltonian simulation, including Trotter type splitting and Magnus expansion based algorithms in the interaction picture. (The talk does not assume a priori knowledge on quantum computing.)

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MS111

Nonadiabatic Dynamics via the Symmetrical Quasi-Classical Method in the Presence of Anharmonicity

The symmetrical quasi-classical (SQC) method is a semiclassical approach that allows one to simulate nonadiabatic dynamics of molecular systems based on an algorithm with classical-like scaling with respect to system size. This is made possible by casting the electronic degrees of freedom in terms of mapping variables that can be propagated in a classical-like manner. While SQC was shown to be rather accurate when applied to benchmark models with harmonic electronic potential energy surfaces, it was also found to become inaccurate and to suffer numerical instabilities when applied to systems with anharmonic degrees of freedom. I will discuss the extension of the original SQC method that overcomes those limitations by describing the anharmonic nuclear modes, which are coupled to the electronic degrees of freedom, in terms of classical-like mapping variables. The accuracy of our approach relative to the standard SQC will be demonstrated on benchmark models with quartic and Morse potential energy surfaces. I will introduce our original approach published in A. Kananenka, C.-Y. Hsieh, J. Cao, and E. Geva, "Nonadiabatic Dynamics via the Symmetrical Quasi-Classical Methodin the Presence of Anharmonicity" J. Phys. Chem. Lett., 9, 319-326 (2018) as well as our recent extensions of the approach.

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MS111

Dynamics of Quantum Molecules in Classical Nonequilibrium Environments

The description of the dynamics of a quantum system coupled to a classical environment, and subject to constraints that drive it out of equilibrium, is the topic of this talk. The evolution of the system is governed by the quantum-classical Liouville equation. The focus of this work is on the derivation of the equations of motion for the nonequilibrium average values of a set operators or variables, along with correlation function expressions for the dissipative coefficients that enter these equations. These equations are obtained by requiring that the exact nonequilibrium averages are equal to local equilibrium averages that depend on auxiliary fields whose values satisfy evolution equations obtained using projection operator methods. The results are illustrated by deriving reaction-diffusion equations coupled to fluid hydrodynamic equations for a dilute solution of quantum particles that can exist in two metastable states. Features of the nonequilibrium reaction rate and diffusion correlation functions will be presented.

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MS111

Koopman Wavefunctions in Classical and Mixed Quantum-classical Mechanics

First appeared in 1931, Koopman's wavefunctions on phase-space provide a formulation of classical mechanics in terms of unitary evolution on a Hilbert space, thereby establishing a suggestive analogy between quantum and classical dynamics. Rediscovered by many over the decades, these functions are now making their appearance in the contexts of quantum computing and molecular dynamics. In the first case, one exploits the analogy with quantum mechanics to devise strategies for the numerical simulation of classical nonlinear dynamics on quantum computers. In the second case, one uses Koopman wavefunctions to approximate nuclei as classical particles, while retaining the electronic quantum fueatures, thereby alleviating the computational costs of molecular simulations for the full electronic-nuclear compound. In the first part, this talk presents the mathematical structure of Koopman wavefunctions in terms of their underlying variational principle. In particular, the use of momentum map structures in geometric mechanics allows to establish the relation between the original Koopman-von Neumann formulation and the so-called Koopman-van Hove construction, which carries additional information about classical phases. The latter plays an important role in the second part of the talk, which focuses on formulating mixed quantum-classical models for problems in computational chemistry. We show that, while current approaches suffer from substantial drawbacks, such as the violation of Heisenberg's principle, these issues can be overcome by using Koopman wavefunctions to model the classical component of a mixed quantum-classical system. As we will see, the resulting dynamics enjoys a Poincar integral invariant leading to the Lie-transport of a mixed quantum-classical symplectic form and its associated Liouville volume. Numerical simulations on molecular problems are presented in the talk by Paul Bergold, who is a collaborator in this project.

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MS112

Vortex Avalanches and Collective Motion in Neutron Stars

We simulate the dynamics of about 600 quantum vortices in a spinning-down cylindrical container using a Gross–Pitaevskii model. For the first time, we find convincing spatial-temporal evidence of avalanching behaviour resulting from vortex depinning and collective motion. During a typical avalanche, about 10 to 20 vortices exit the container in a short period, producing a glitch in the superfluid angular momentum and a localised void in the vorticity. After the glitch, vortices continue to depin and circulate around the vorticity void in a similar manner to that seen in previous point-vortex simulations. We present evidence of collective vortex motion throughout this avalanche process. We also show that the effective Magnus force can be used to predict when and where avalanches will occur. Lastly, we comment on the challenge of extrapolating these results to conditions in real neutron stars, which contain many orders of magnitude more vortices.

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MS112

The Phase Space of the Three-Vortex Problem and Its Application to Vortex-Dipole Scattering

The three-vortex problem was shown to be integrable by Grbli in 1877. His reduced dynamics, describing a system of three equations for the pairwise distance between vortices, has been rediscovered several times since. This system is singular whenever the three vortices are collinear, which makes applying standard phase-plane reasoning difficult. We derive a new system of equations using Jacobi coordinates followed by Lie-Poisson reduction. This leads to an effectively one-degree-of-freedom integrable system with no such coordinate singularities. We apply this system to several problems: vortex-dipole scattering, the complete classification of the dynamics, a related integrable four-vortex problem, and dipole-dipole scattering.

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MS112

Hamiltonian Dynamics in Three Dimensional Geophysical Vortices

Geophysical turbulent flows, characterized by rapid rotation (quantified by small Rossby number) and stable stratification, self-organize into collections of coherent vortices. The lowest-order asymptotic expansion in Rossby number is quasigeostrophy (QG) with purely horizontal velocities, cycloneanticyclone antisymmetry, and well-known Hamiltonian point vortex solutions. The next-order correction in Rossby number, balance dynamics, includes ageostrophic vertical velocity and cyclone-anticyclone asymmetry. Counter-rotating vortex pairs, hetons, travel long distances and trap fluid as they move. QG hetons induce a 3D velocity field with Hamiltonian structure which governs the transport of trapped fluid. The dynamics displays a sequence of bifurcations moving through the velocity field in height. The bifurcations create and destroy unstable fixed points whose associated invariant manifolds bound the trapped volume. We find point vortex solutions in a particular formulation of 3d balance dynamics, QG^{+1} dynamics. Simulations of QG^{+1} point vortices show significant vertical transport on long time scales. The trajectories of QG^{+1} point vortices appear to have Hamiltonian structure, but the Hamiltonian has not yet been found. Balance dynamics does have a Hamiltonian formulation but point vortex solutions have not yet been found in that formulation. We hypothesize that ageostrophic point vortices have a Hamiltonian structure awaiting discovery.

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MS113

Mechanisms for Entrainment in Deep Brain Stimulation Treatment for Parkinsons Disease

Deep brain stimulation (DBS) is used in Parkinsons Disease to alleviate symptoms and improve quality of life. First implemented more than 60 years ago, now more than 25,000 devices are implanted annually. In DBS, electric leads are implanted in, for example, the subthalamic nucleus (STN) of the brain. Typically, electric stimulation is applied 24 /7 with pulses of a fixed width, amplitude and frequency. State-of-the-art devices are estimated to alleviate symptoms 60% of the time. Mechanisms by which DBS works are largely unknown, limiting the ability to further improve symptom control. Recent work has made at least three important steps. First, on medication some patients exhibit a peak in the electrocortical activity in a narrow gamma band $\sim$ (60–90 Hz). Second, in the presence of stimulation the gamma band peak is enhanced and shifts to half the stimulation frequency. Third, a mechanistic mathematical model that explains the shift in terms of entrainment has been developed. However, open questions remain as to the robustness of the approach. Here we present our analysis of mathematical models for DBS, with the focus on entrainment mechanisms. Our long-term goal is to inform the future design of closed-loop DBS devices that adapt to patient need in real time.

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MS113

Travelling Waves Through Spiking Neuronal Networks with Voltage-gated Ion Channels

Travelling waves of firing activity are a well-attested and robust mode of interaction across neural populations. From a mathematical perspective, travelling waves are an analytically tractable behaviour even on large networks of individually-modelled neurons. Here, we examine the existence and stability of multi-spike travelling waves in networks of leaky integrate-and-fire neurons with local adaptation such as that mediated by voltage-gated ion channels. This allows us to study the relationship between the neurons internal dynamics as modulated by the ion channels and the network-wide dynamics represented by the travelling wave. We observe that the ion channel plays a conditional self-excitatory role, promoting and stabilising faster waves until the solution branch is lost due to the emergence of additional firing events. In certain parameter ranges we observe the disconnection of solution branches, opening gaps in the range of possible wave speeds. We present this work upon one-dimensional networks with an eye towards extension into higher dimensions.

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MS113

Desynchronizing Populations of Neural Oscillators

Deep brain stimulation is a therapeutic treatment for a variety of neurological disorders such as Parkinsons disease, which is hypothesized to be due to pathological synchronization of neural activity in the motor control region of the brain. This motivates the control objective of desynchronizing neural activity using a single electrical stimulus. Challenges include high-dimensionality, nonlinear effects, underactuation, and constraints on allowable control inputs. Various approaches have been developed to overcome these challenges, including chaotic desynchronization in which the control is chosen to maximize the Lyapunov exponent associated with phase differences for the neurons, optimal phase resetting in which an input drives the system to the phaseless set where the neurons are particularly sensitive to noise, and phase density control in which an input drives the system toward a desired phase distribution. This presentation will discuss these approaches, including recent extensions of prior work.

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MS113

Modelling UV Avoidance Circuits in the Platyneiris Worm

The seaworm platyneiris dumerilii offers exciting prospects to study intact neuronal circuits given its relatively simple neural architecture and its ease of genetic manipulation. In particular, the connectome for the platyneiris has been fully mapped, presenting opportunities to study the link between neuronal activation and functional behaviour in an organism with more complexity than in seminal studies of C. elegans. In this talk, I will discuss preliminary modelling work to investigate UV avoidance responses in platyneiris, measured using in vivo calcium imaging of photoceptor neurons and their adjacent interneurons. In particular, we will consider the role of a key chemical messenger, nitric oxide, involved in feedback regulation of this simple motor circuit under stimulation of different light stimulation patterns. Our model is used to predict responses to such experiments, which are then tested in genetic mutants of the platyneiris to disentangle the specific role of nitric oxide feedback.

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MS114

Attraction and Synchronization in Markov RDS on Discrete Space

Random attractors and synchronization of (Markov) RDS have been extensively studied on metric spaces, yielding a wide range of phenomena with sometimes only subtle differences. On discrete spaces it turns out that the picture is much simpler: A random attractor exists, is unique, and forward and pullback attraction are equivalent. In this talk we consider the time until an initial condition reaches the attractor and the time until two initial conditions synchronize (if they do). The methodology for proving a finite expectation for these random times involves the construction of a Lyapunov function for the two-point motion, and a careful coupling argument.

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MS114

Zero Lyapunov Exponent Implies Synchronization on Average for Some Random Circle Endomorphisms

In this talk we establish the existence of intermittent 2-point dynamics and infinite ergodic invariant measures for a class of random circle endomorphisms with zero Lyapunov exponent, as a dynamical characterisation of the transition from synchronisation (negative Lyapunov exponent) to chaos (positive Lyapunov exponent). This is a joint work with J.S.W. Lamb and A.J. Homburg.

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MS114

Randomly Switched Dynamics

TBD

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MS115

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 showcase 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.

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MS115

Stability of Smooth Solutions to Peakon Equations

The Camassa-Holm equation was originally derived as an asymptotic equation in shallow water wave theory. Among its interesting mathematical properties, perhaps the most striking is the fact that it admits weak soliton solutions - peakons- with a peaked shape corresponding to a discontinuous first derivative. Since the discovery of the Camassa-Holm equation, several peakon equations with similar properties, both in the integrable and non-integrable cases have been studied. Among them, there is the integrable Novikov equation, which can be regarded as a generalization to a cubic nonlinearity of the Camassa-Holm equation. Furthermore, both the Camassa-Holm and the Novikov equations each admit a generalization taking the form of a one-parameter family of peakon equations, most of which are not integrable. In this talk, we study the spectral and orbital stability of various smooth solutions to peakon equations. One of the main difficulties when dealing with the linear operators arising from peakon equation is that they often include a non-local term. An additional challenge is the fact that the localized smooth solutions admit a nonzero background.

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MS115

The Duistermaat Index and Eigenvalue Interlacing for Self-Adjoint Extensions of a Symmetric Operator

Eigenvalue interlacing is a useful tool in linear algebra and spectral analysis. In its simplest form, the interlacing inequality states that a rank-one positive perturbation shifts each eigenvalue up, but not further than the next unperturbed eigenvalue. We prove a sharp version of the interlacing inequalities for finite-dimensional perturbations in boundary conditions, expressed as bounds on the spectral shift between two self-adjoint extensions of a fixed symmetric operator with finite and equal defect numbers. The bounds are given in terms of the Duistermaat index, a topological invariant describing the relative position of three Lagrangian planes in a symplectic space. Two of the Lagrangian planes describe the self-adjoint extensions being compared, while the third corresponds to the Friedrichs extension, which acts as a reference point.

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MS115

Spatial Heterogeneity and Striped Phases

I will discuss the effect of spatial inhomogeneities on striped phases, focusing mostly on spatially localized disturbances but as time permits mention spatial gradients. Technically, the problem here is to describe a "spatial center manifold" at spatial infinity and asymptotics of solutions within this manifold, in particular when spatial infinity is higher-dimensional. Our results describe these dynamics in terms of multipole expansions but also point to a more general algebra for these infinite-dimensional asymptotics.

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MS116

Prediction Skill and Predictability of Extreme Events Using Machine Learning Derived Large Ensembles

Accurately predicting extreme weather events remains a significant challenge due to ensemble size limitations and calibration constraints in traditional forecasting methods. This study leverages realistic initial conditions (ICs) in combination with an artificial intelligence-based numerical weather prediction (AI-NWP) system and generative diffusion models for ensemble expansion, improving the capture and prediction of rare, high-impact events, such as atmospheric rivers. Our approach employs a two-phase forecasting framework that integrates NOAA-provided ICs and post-processes forecasts with diffusion models, generating a broader distribution of possible atmospheric states. Rigorous evaluation against NOAAs operational metrics will assess improvements in calibration, probabilistic skill, and extreme event accuracy, aiming to transfer the methodology to operational systems. By advancing AI-driven ensemble forecasting, this study enhances predictive skills for low-probability, high-impact events, refining understanding of critical variables and dynamics and supporting informed decision-making for extreme weather preparedness.

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MS116

Combining Flux Limiters and Machine Learning to Parametrize Subgrid Scales in the Shallow Water Equation

We consider a one-dimensional shallow-water equation and develop a subgrid parametrization scheme by combining machine learning and flux limiters. The developed Neural Network parametrization is local in space and is represented in flux form, thus allowing the application of flux limiters to ensure physically relevant solutions. We demonstrate the applicability of our approach for the inviscid, as well as forced and damped regimes of the shallow-water equations.

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MS116

A Closed-Form Nonlinear Data Assimilation Algorithm for Multi-Layer Flow Fields

State estimation in a multi-layer flow field by only observing the up-most layer information is a challenging but practically important topic. Applications include inferring the state of the deep ocean by exploiting surface observations. One widely used method is to build a regression model between the state variables in different layers. However, when the flow field is highly turbulent, the accuracy of the regression solution will suffer from large uncertainty. In this work, we introduce a new nonlinear data assimilation (DA) method. A sequence of nonlinear DA is applied from the upper layer to the lower one recurrently. The nonlinear DA captures the features of the strong turbulence in the underlying dynamics and can accurately quantify the uncertainty. Despite nonlinearity, closed analytic solutions are available for the DA solution. The estimated state is given by a non-Gaussian distribution using Gaussian mixtures, capturing intermittency and extreme events. The method can also be adaptive to the situation with parameter estimation. It applies to estimating the bottom topography in the deep ocean simultaneously with the state estimation.

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MS117

Plasmid Loss in Spatially Constrained Microbial Populations

Bacterial cells contain extrachromosomal DNA molecules called plasmids. In nature, plasmids often confer antibiotic resistance. Cells commonly have no mechanism for evenly partitioning plasmids during cell division, and thus there is some probability that one of two daughter cells does not inherit any plasmids. On the population scale, what factors influence the persistence of plasmid DNA over generations? Mathematical modeling is useful in answering this question, as it is difficult to experimentally resolve new plasmid loss from replication of previously plasmid-free cells over long time periods. We introduce a spatial Moran-like model of a finite cell population undergoing plasmid loss, because biologists frequently observe cell populations in spatially constrained microfluidic traps. We explore how properties of single cells impact the dynamics of the cell population in different trap geometries. This analysis reveals that the persistence of plasmid DNA in cell populations has a complex dependence on both spatial geometry and assumptions on single cell properties such as cell division age.

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MS117

Cellular Heterogeneity and Dynamic Perturbations Preceding Cytokinesis Failure

The stability of cell division cycle is essential for maintaining genomic integrity. Perturbations in the mechanisms that regulate the cell cycle can result in abnormal cellular phenotypes, such as multinucleated cells, which are implicated in cancer progression due to their role in genomic instability and metastasis. This study focuses on MCF10A human mammary epithelial cells which, when exposed to transforming growth factor beta (TGF), undergo epithelial- mesenchymal transition (EMT). Under stiff microenvironmental conditions, the process of EMT increases cytokinesis failure and multinucleation. Using quantitative time-lapse imaging, we analyzed the spatiotemporal dynamics of cells that produce multinucleated progeny, focusing on cell-cycle progression, nuclear morphology, and motility. Our results demonstrate that cytokinesis failure is preceded by variability in cell-cycle duration and nuclear morphology. Mothers of multinucleated progeny exhibit irregular cell cycles, nuclear pleomorphism, and persistent motility, suggesting a disruption in cellular homeostasis. Despite similar mean population behaviors, increased heterogeneity on the single-cell level may contribute to their invasiveness and treatment resistance. Our findings highlight the role of intracellular noise in shaping population-level outcomes, providing insights into the stochastic nature of multinucleation and its implications for tumor progression and therapeutic strategies.

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MS117

First Passage Time Problems in Chromosome Segregation

Chromosome segregation is a complex and highly regulated process critical to cell division. This talk will describe theoretical insights from two projects focused on the mechanisms that ensure chromosome segregation fidelity. In the first project, we study the partitioning of N=46 chromosome pairs into the two daughter cells, for wild-type cells, in the presence of drug and genetic perturbations, and for cancer cells. We model the process as a first passage time problem using a generalization of a model introduced by Ehrenfest a century ago in the context of the second law of thermodynamics. Our model allows us to evaluate the error correction rate and the spindle assembly checkpoint (SAC) reliability. We found that while certain SAC-regulating proteins influence anaphase timing and checkpoint function, they do not alter the error correction rate. In the second project, we use the same mathematical model albeit at a completely different scale, describing the intercellular mechanisms of microtubule attachment and detachment (that, in turn, are an integral part of the functioning of the mitotic spindle). Together, these showcase the utility of statistical physics and stochastic processes in fundamental problems of cell biology.

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MS117

What to do if You Miss a Dose of Antibiotics?

Despite the prevalence of missed antibiotic doses, there is vague or little guidance on what to do when a dose is forgotten. In this presentation, we consider the effects of different patient responses after missing a dose using a mathematical model that links antibiotic concentration with bacteria dynamics. We show using simulations that, in some circumstances, (a) missing just a few doses can cause treatment failure, and (b) this failure can be remedied by simply taking a double dose after a missed dose. We then develop an approximate model that is analytically tractable and use it to understand when it might be advisable to take a double dose after a missed dose.

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MS118

A Mechanistic Model of Gossip, Reputations, and Cooperation

Social reputations facilitate cooperation: those who help others gain a good reputation, making them more likely to receive help themselves. But when people hold private views of one another, this cycle of indirect reciprocity breaks down, as disagreements lead to the perception of unjustified behavior that ultimately undermines cooperation. Theoretical studies often assume population-wide agreement about reputations, invoking rapid gossip as an endogenous mechanism for reaching consensus. However, the theory of indirect reciprocity lacks a mechanistic description of how gossip actually generates consensus. Here, we develop a mechanistic model of gossip-based indirect reciprocity that incorporates two alternative forms of gossip: exchanging information with randomly selected peers or consulting a single gossip source. We show that these two forms of gossip are mathematically equivalent under an appropriate transformation of parameters. We derive an analytical expression for the minimum amount of gossip required to reach sufficient consensus and stabilize cooperation. We analyze how the amount of gossip necessary for cooperation depends on the benefits and costs of cooperation, the assessment rule (social norm), and errors in reputation assessment, strategy execution, and gossip transmission. Finally, we show that biased gossip can either facilitate or hinder cooperation, depending on the direction and magnitude of the bias.

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MS118

Hypergraph Reconstruction from Dynamics

A plethora of methods have been developed in the past two decades to infer the underlying network structure of an interconnected system from its collective dynamics. However, methods capable of inferring nonpairwise interactions are only starting to appear. Here, we develop an inference algorithm based on sparse identification of nonlinear dynamics (SINDy) to reconstruct hypergraphs and simplicial complexes from time-series data. Our model-free method does not require information about node dynamics or coupling functions, making it applicable to complex systems that do not have a reliable mathematical description. We first benchmark the new method on synthetic data generated from Kuramoto and Lorenz dynamics. We then use it to infer the effective connectivity in the brain from resting-state EEG data, which reveals significant contributions from non-pairwise interactions in shaping the macroscopic brain dynamics.

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MS119

Dynamics of Female Gender Representation in Academic Mathematics

Well into the 21st century, women remain underrepresented in academic mathematics. In this project, we study the dynamics of female gender representation among the faculty of doctorate-granting mathematics departments. We abstract academic genealogies as a multitype branching process in which advisors generate graduated PhD students, and estimate the parameters of this process by fitting a mechanistic model of academic careers to a data set derived from the Mathematics Genealogy Project. Upon fitting our model, we find that male academics enjoy an advantage in production of new PhD students relative to their female colleagues, and that this influences the next generation due to homophily effects. Our formalism suggests that, without substantial structural shifts, gender representation in most subfields of mathematics will increase slightly before leveling out well short of parity. We close with some reflections on our models limitations and what it suggests about interventions to the representation of women in academic mathematics.

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MS119

Unpacking Climate Polarization Across News and Social Media

Since the late 1980s, climate change has become a deeply polarizing issue in the United States. This phenomenon is complex. Despite broad public support for climate policies, this support is often underestimated, undermining efforts to build coalitions for effective implementation. News outlets and social media platforms play a central role in shaping public understanding and narratives around climate change but often exacerbate polarization through selective framing. In this work, we investigate the complexities of climate polarization by analyzing both news and social media. Using a corpus of 2,072 U.S. TV news transcripts, we map how climate policies are framed in mainstream media. Additionally, we analyze the structure of Reddit communities to quantify climate polarization, examining how technologies, policies, and behaviors are discussed. We identify key topics, such as sustainable diets, renewable energy, climate concern, and public transit, and map these issues onto the political spectrum to reveal their intersections with partisan discourse. By identifying narratives and framing strategies that promote bipartisan support, this study lays the groundwork for predictive modeling of interventions that can help amass support for climate action.

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MS119

Model Design and Systematic Biases in Contagion Dynamics

Social contagion dynamics are often modeled using a peer pressure mechanism: the more individuals are exposed to "contagious" peers, the more likely they are to adopt the opinion or behavior, in a nonlinear fashion. In many instances, this social reinforcement mechanism even takes the form of a discontinuous adoption threshold. Characterizing this nonlinear adoption mechanism from data, however, proves challenging. In this presentation, we will explore the role of modeling assumptions in shaping the results of the inferences we make about a stochastic contagion process. More specifically, we will show how heterogeneities, whether hidden or ignored by the modeler, drive a systematic bias toward more "nonlinear" contagion mechanisms. These results more broadly highlight the crucial role of model design and its impact on our mechanistic understanding of dynamical processes. This cautionary tale about inference is especially important if the same model is then used to make predictions, which might be completely wrong if the true underlying mechanisms are not well captured by the model structure.

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MS119

Scientific Productivity As a Random Walk

The expectation that scientific productivity follows regular patterns over a career underpins many scholarly evaluations, including hiring, promotion and tenure, awards, and grant funding. However, recent studies of individual productivity patterns reveal a puzzle: on the one hand, the average number of papers published per year robustly follows the "canonical trajectory" of rapid rise to an early peak followed by a graduate decline, on the other hand, only about 20% of individual researchers' productivity follows this pattern. We resolve this puzzle by modeling scientific productivity as a parameterized random walk, showing that the canonical pattern can be explained as a decrease in the variance in changes to productivity in the early-to-mid career. By empirically characterizing the variable structure of 2,085 productivity trajectories of computer science faculty at 205 PhD-granting institutions, spanning 29,119 publications over 1980–2016, we (i) discover remarkably simple patterns in both early-career and year-to-year changes to productivity, and (ii) show that a random walk model of productivity reproduces the canonical trajectory in the average productivity and captures much of the diversity of individual-level trajectories. These results highlight the fundamental role of a panoply of contingent factors in shaping individual scientific productivity, opening up new avenues for characterizing how systemic incentives and opportunities can be directed for aggregate effect.

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MS120

Interacting Particle Systems on Networks: Joint Inference of the Network and the Interaction Kernel

Modeling multi-agent systems on networks is a fundamental challenge in a wide variety of disciplines. We jointly infer the weight matrix of the network and the interaction kernel, which determine respectively which agents interact with which others and the rules of such interactions from data consisting of multiple trajectories. The estimator we propose leads naturally to a non-convex optimization problem, and we investigate two approaches for its solution: one is based on the alternating least squares (ALS) algorithm; another is based on a new algorithm named operator regression with alternating least squares (ORALS). Both algorithms are scalable to large ensembles of data trajectories. We establish coercivity conditions guaranteeing identifiability and well-posedness. The ALS algorithm appears statistically efficient and robust even in the small data regime but lacks performance and convergence guarantees. The ORALS estimator is consistent and asymptotically normal under a coercivity condition. We conduct several numerical experiments ranging from Kuramoto particle systems on networks to opinion dynamics in leader-follower models.

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MS120

Mori-Zwanzig Mode Decomposition: Applications in Laminar-turbulent Transition

We introduce the Mori-Zwanzig (MZ) Modal Decomposition (MZMD), a novel technique for performing modal analysis of large scale spatio-temporal structures in complex dynamical systems, and show that it represents an efficient generalization of Dynamic Mode Decomposition (DMD). The MZ formalism provides a mathematical framework for constructing non-Markovian reduced-order models of resolved variables from high-dimensional dynamical systems, incorporating the effects of unresolved dynamics through the memory kernel and orthogonal dynamics. We present a formulation and analysis of the modes and spectrum from MZMD and compare it to DMD and Higher-order DMD when applied to a complex flows for modelling laminar-turbulent boundary-layer transition of hypersonic flows. We show that the addition of memory terms by MZMD improves the resolution of spatio-temporal structures within the transitional/turbulent regime, which contains features that arise due to nonlinear mechanisms, such as the generation of the so-called "hot" streaks on the surface of the flared cone.

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MS120

Learning Soft Matter Dynamics from Experimental Data: Reduced Order Models and Frame Invariance

Soft materials are widely used in existing and emerging technologies, but their complex dynamical response to mechanical deformation pose challenges in systematic design of new materials. The dynamics are intrinsically multiscale due to the coupling of the microscopic molecular conformations to the macroscale flow. Furthermore, soft matter systems are characterized by disorder and lack of pristine observations from experiment or simulation. We present methods leveraging machine learning and inertial manifold theory to learn reduced order models directly from experimental scattering and birefringence data. We emphasize the importance of encoding mechanical symmetries and constraints such as frame indifference and Euclidean invariance.

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MS121

State-dependent Neural Encoding of Behavior in Freely Moving C. Elegans: a Bayesian Approach

To thrive in changing conditions, animals need to optimize their foraging strategy as a function of resource distribution, recent experience, and internal needs. Such a rich behavioral repertoire suggests the presence of highly flexible neural substrates. The relationship between neural activity and behavior can change across internal states, reflecting a flexible internal representation of the environment and self-driven actions. Using a probabilistic encoding framework, we quantify how the activity of genetically defined neuron classes can be described with a set of behavioral features, and how such encoding depends on internal variables such as feeding history. Past work in our lab proposed the C. elegans Probabilistic Neural Encoding Model (CePNEM), which predicted neural activity from calcium imaging as a function of an animal's recent behavior (Atanas, Kim et al., 2023). From parameter posterior distributions, we can isolate true behavior feature encodings from spurious correlations and motion artifacts. Our current work seeks to unveil state-dependence in neural encoding by fitting a hierarchical model across many animals in different internal states, and allowing each model parameter to arise from a mixture of probable values. Neurons that encode behavior with different sets of model parameters in different states represent flexible nodes in the system. Synchronized switches can reveal the origin of neural flexibility that gives rise to adaptive behaviors.

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MS121

Degeneracy in Brain-Body-Environment Systems

Variability is a fundamental aspect of biological systems. Adopting a brain-body-environment perspective, we observe degeneracy at multiple levels: different neural circuits can yield similar activity patterns, which in turn can produce analogous behaviors that achieve similar fitness outcomes. This talk uses C. elegans locomotion to explore variability and degeneracy in whole-organism models. Rather than seeking a singular "correct" locomotion circuit, we aim to identify all possible circuits capable of generating locomotion behavior. Specifically, we investigate circuits that produce mixed pattern generation, functioning robustly with and without stretch-receptor feedback. We expand our analysis beyond the complete connectome, considering the Ventral Nerve Cord's uncharted sections, ongoing variability despite identified patterns, and the limited reconstruction of connectomes across individuals, which suggests significant individual and lifetime variability. We will present our brain-body-environment neuromechanical model and a novel stochastic search and ensemble approach, discussing insights gained about degeneracy in mixed pattern generation within C. elegans and broader implications for understanding variability in biological systems.

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MS121

Deep Generative Modeling for Identification of Noisy, Non-Stationary Dynamics for Nematode C. Elegans Locomotion and for Other Systems

Theoretical neuroscience suggests that interactions between neurons or networks in the nervous system can be described by nonlinear dynamics. Traditionally, dynamical systems theory models these interactions through differential equations (ODEs), providing interpretable insights into how brain processes evolve into network dynamics. More recently, machine learning models like recurrent neural networks (RNNs) and variational autoencoders (VAEs) have been used to study neural dynamics, though they often lack interpretability. This study combines VAEs with ODEs to analyze Calcium activity in C. elegans during movement. VAEs extract key features and generate time series for coefficients in an ODE system that describes the first two principal components of the data. Using the SINDy (sparse identification for nonlinear dynamics) framework, we identify the ODE by combining the VAE output coefficients with a polynomial function library, and applying sparsity regularization to ensure simplicity. The resulting ODE has a switching parameter and captures key behavioral phases, with stable states for forward and backward crawling and transitions for turning movements. This method blends deep learning with differential equations, offering a new approach to characterizing complex dynamics that could extend to other organisms and behaviors.

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MS121

Uncovering Nonstationary Dynamics in C. Elegans with Decomposed Linear Dynamical Systems

Biological neural networks are non-linear, non-stationary systems where multiple sub-circuits interact at different spatial and temporal scales to produce complex behaviors. Even smaller model organisms have highly complex neural activity. For example C. elegans, with their 302 neurons, produce fluctuating dynamics that adapt and change, even defying the architecture of the connectome (Randi et al. 2023). Current modeling frameworks fail to capture these critical properties and 1) are limited to stationary systems, 2) cannot identify independent sub-systems with distinct functional roles, and 3) are often challenging to interpret, especially for most highly expressive network models (e.g., recurrent neural networks). We thus developed a new dynamical systems framework, decomposed Linear Dynamical Systems (dLDS) to address these gaps. dLDS models dynamics as trajectories on a low-dimensional manifold. The trajectories thus locally move in the direction of the tangent spaces, providing a linear space in which to model the time-varying dynamics at each time-point F_t as a decomposition in a dictionary of time-invariant dynamics that are learned from the data $\sum_k f_k c_{kt}$. To induce interpretability, we orient the dynamics dictionary directions with the flow of the trajectories via a sparsity assumption on the coefficients c_{kt}. In C. elegans, dLDS reveals highly adaptive motifs of interactions that change between bouts, worms, and experimental epochs.

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MS122

Fluctuations in Wasserstein Dynamics on Graphs

We propose a drift-diffusion process on the probability simplex to study stochastic fluctuations in probability spaces. We construct a counting process for linear detailed balanced chemical reactions with finite species such that its thermodynamic limit is a system of ordinary differential equations (ODE) on the probability simplex. This ODE can be formulated as a gradient flow with an Onsager response matrix that induces a Riemannian metric on the probability simplex. After incorporating the induced Riemannian structure, we propose a diffusion approximation of the rescaled counting process for molecular species in the chemical reactions, which leads to Langevin dynamics on the probability simplex with a degenerate Brownian motion constructed from the eigen-decomposition of Onsager's response matrix. The corresponding Fokker-Planck equation on the simplex can be regarded as the usual drift-diffusion equation with the extrinsic representation of the divergence and Laplace-Beltrami operator. The invariant measure is the Gibbs measure, which is the product of the original macroscopic free energy and a volume element. When the drift term vanishes, the Fokker-Planck equation reduces to the heat equation with the Laplace-Beltrami operator, which we refer to as canonical Wasserstein diffusions on graphs. In the case of a two-point probability simplex, the constructed diffusion process is converted to one dimensional Wright-Fisher diffusion process.

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MS122

Bounded Krnet and Its Applications to Density Estimation and Approximation

In this work, we develop an invertible mapping, called B-KRnet, on a bounded domain and apply it to density estimation/approximation for data or the solutions of PDEs such as the Fokker-Planck equation and the Keller-Segel equation. Similar to KRnet, the structure of B-KRnet adapts the pseudo-triangular structure into a normalizing flow model. The main difference between B-KRnet and KRnet is that B-KRnet is defined on a hypercube while KRnet is defined on the whole space, in other words, a new mechanism is introduced in B-KRnet to maintain the exact invertibility. Using B-KRnet as a transport map, we obtain an explicit probability density function (PDF) model that corresponds to the pushforward of a prior (uniform) distribution on the hypercube. It can be directly applied to density estimation when only data are available. By coupling KRnet and B-KRnet, we define a deep generative model on a high-dimensional domain where some dimensions are bounded and other dimensions are unbounded. A typical case is the solution of the stationary kinetic Fokker-Planck equation, which is a PDF of position and momentum. Based on B-KRnet, we develop an adaptive learning approach to approximate partial differential equations whose solutions are PDFs or can be treated as PDFs. A variety of numerical experiments is presented to demonstrate the effectiveness of B-KRnet.

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MS122

Score-Based Neural Ordinary Differential Equations for Computing Mean Field Control Problems

Classical neural ordinary differential equations (ODEs) are powerful tools for approximating the log-density functions in high-dimensional spaces along trajectories, where neural networks parameterize the velocity fields. We proposes a system of neural differential equations representing first- and second-order score functions along trajectories based on deep neural networks. We reformulate the mean field control (MFC) problem with individual noises into an unconstrained optimization problem framed by the proposed neural ODE system. Additionally, we introduce a novel regularization term to enforce characteristics of viscous HamiltonJacobiBellman (HJB) equations to be satisfied based on the evolution of the second-order score function.

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MS123

Warning Signs for Boundary Noise: Construction and Application to An Ocean Model

The use of early-warning signs is justified in applications characterized by abrupt transitions, such as climate science, to predict the corresponding highly impactful changes. While early-warning indicators such as increased variance and autocorrelation are well-established for one-dimensional models with additive noise, their application in complex systems governed by stochastic partial differential equations (SPDEs) presents new challenges. This talk discusses novel methodologies for implementing early-warning signs with a focus on an ocean Boussinesq model designed to simulate the potential collapse of the Atlantic Overturning Meridional Circulation (AMOC). The model incorporates boundary additive Gaussian noise to account for subtle influences in the Greenland Ice Sheet melt and salinity changes in the North Atlantic Ocean. We explore how these methods can enhance predictive capabilities in SPDE-based models, aiming to improve risk assessment and proactive decision-making.

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MS123

Negative Regularity Mixing for Advection by Random Velocities

This talk examines the long-time behavior of a passive scalar advected by an incompressible velocity field. While exponential decay in anisotropic Sobolev spaces is well-established for uniformly hyperbolic flows, this approach does not extend to the non-autonomous and non-uniformly hyperbolic setting. We present a framework for analyzing scalar decay in the context of stochastic velocity fields. By leveraging pseudo-differential operators, we establish averaged decay estimates, demonstrating a "low regularity mixing" property from $H^{-\delta} \to H^{-\delta}$ that is unique to the stochastic setting. This result enables us to demonstrate, under specific conditions on the velocity field, the existence of a unique stationary measure for the Markov process generated by the advection equation with a random source term. This measure characterizes the statistics of "ideal" scalar turbulence.

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MS123

Lower Bounds to Lyapunov Exponents in Stochastic Pdes

We consider a passive scalar advected by a stochastic velocity field. Under some non-degeneracy assumptions on the noise, we prove a lower bound on the energy dissipation that is quantitative in the diffusivity of the scalar. This partially addresses a conjecture by Miles and Doering and proves a first lower bound to the so-called Batchelor scale. The proof is based on dynamics of energy level sets, and a refined short- time and high-frequency expansion. Joint work with M. Hairer, S. Punshon-Smith and J. Yi.

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MS124

Constructing a Cerebral Hemodynamics Model Within a Data Assimilation Pipeline to Enhance Clinical Decision Support in Neurocritical Care

The brain requires continuous and adequate cerebral blood flow (CBF) to survive. In healthy conditions, CBF is controlled by multiple physiologic mechanisms, collectively known as cerebral vascular tone regulation (CVTR). Brain injuries impact CBF and CVTR mechanisms, thereby impacting patient outcomes. Quantifying CVTR functionality and forecasting CBF could be transformative for clinical decision support by informing personalized therapy to maximize the functional outcome of neurological injury patients. We constructed and validated a novel ordinary differential equations model (CVTR model) of cerebral hemodynamics that explicitly includes the action of CVTR mechanisms. We built this model into a data assimilation framework to estimate parameters (called computational CVTR biomarkers), which are mathematical representations of a patient's CVTR functionality. Using simulated and experimental data, we showed that the CVTR computational biomarkers were uniquely estimable for all patient phenotypes using Markov Chain Monte Carlo (MCMC) optimization. We used MCMC to estimate CVTR computational biomarkers for five traumatic brain injury patients. CVTR biomarkers were predictive of patient outcomes and unique. We also used these CVTR biomarkers to simulate CBF forward up to an hour. The CVTR model forecast had superior accuracy than the canonical cerebral hemodynamics model, a neuralODE, and multivariate linear regression.

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MS124

Sex Differences in the Dynamics of Type-2 Diabetes Pathogenesis

Type 2 diabetes (T2D) is a metabolic disorder that can lead to serious health complications. The oral glucose tolerance test (OGTT) is commonly used to diagnose T2D, but it follows a one-size-fits-all approach by administering a fixed glucose load. However, T2D progression differs between women and men, as reflected in varying OGTT results. Research suggests that when body size is accounted for, some of the observed sex differences in OGTT outcomes are diminished, highlighting the need for a diagnostic tool that accounts for body size to better capture sex-specific variations in T2D pathogenesis. To address this, it is important to quantify the impact of the one-size-fits-all approach on diagnostic outcomes. Physiological models of blood glucose (BG) dynamics include parameters for insulin secretion, sensitivity, and body size (e.g., body weight), which can be tailored to individual patients to improve metabolic characterization. In this study, we used a dynamical system model of BG dynamics during the OGTT to assess how body size affects glucose metabolism. We estimated parameters related to insulin secretion and sensitivity by (1) assuming a fixed body weight of 75 kg and (2) using participants' actual body weights from OGTT data. Our results show that the one-size-fits-all approach may contribute to the observed sex differences in T2D progression. Accurately understanding these differences requires distinguishing the effects of sex and body size on T2D diagnostic markers.

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MS124

Data Assimilation Through a Model-Supported Optimal Transport Barycenter Problem

This talk explores a new methodology for data assimilation, combining the robustness and fidelity to the data of simulation based on the Wasserstein barycenter problem with the interpretability and use of field-knowledge of a model-based approach. The two approaches are blended through a barycenter problem where the transportation cost is measured not from the original state variables but from modified values that eliminate the variability that a knowledge-based model can explain. The methodology includes a first-principled way to account for latent variables. It links observations to the corresponding state values through a multi-component objective function that takes into account both point and distribution wise discrepancies between the two.

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MS124

Computing and Forecasting Model Parameters of Physiological Mechanics for Next-Generation Clinical Decision Support (CDS)

Predicting outcomes of interventions that often depend on the individual patient can be complicated forecast problems. These forecast problems rely in part on health care professionals' (HCPs) deep understanding of physiological and pharmacological mechanisms. Different physiological information evolve on different time scales relevant to the roles of different HCPs. This decision-making process requires balancing population-scale medical knowledge and clinical reasoning from individual health outcomes. Available physiological data are extremely sparse, leaving the system relatively unspecified for HCPs and any potential computational method. This data sparsity problem implies the difficulty for computational methods to extract detailed physiological information and make operationally useful forecasts. Mechanistic models of physiological system(s) provide a pathway to compensate for data sparsity by representing our mathematized understanding of physiological dynamics and processes at multiple time scales. Estimating model parameters and states with individual data using reduces the impact of data sparsity by leveraging the physiologically-allowable relationships and time evolution rules that are hard-coded into model equations. To support next-generation CDS, we develop a data assimilation (DA) and machine learning (ML) hybrid pipeline for computing and forecasting underlying physiological processes of individual patient at slow-evolving time scales relevant to HCP roles.

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MS125

Using Phase Response Curves for Noise-Driven Neural Rhythms to Analyse Emergent Spatial-Temporal Coherence States

Phase reduction is an important tool for studying coupled and driven oscillators. The question of how to generalize phase reduction to stochastic oscillators remains actively debated. In this work, we propose a method to derive a self-contained stochastic phase equation of the form $d\vartheta = a_\vartheta(\vartheta)dt + \sqrt{2D_\vartheta(\vartheta)}\,dW_\vartheta(t)$ that is valid not only for noise-perturbed limit cycles, but also for noise-induced pseudocycles. We show that our reduction captures the asymptotic statistics of qualitatively different stochastic oscillators, and use it to infer their phase-response properties.We further show how this reduction can be used to analyse the structure of neural systems and also to lead to phase response functions for excitable neural systems with noise induced rhythms.

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MS125

Koopman Eigenfunctions, Synchronization, and

Arnold Tongues for Coupled Stochastic Oscillators

Phase reduction is a well-established method to study weakly driven and weakly perturbed oscillators. Traditional phase-reduction approaches characterize the perturbed system dynamics solely in terms of the timing of the oscillations. In the case of large perturbations, the introduction of amplitude (isostable) coordinates improves the accuracy of the phase description by providing a sense of distance from the underlying limit cycle. Importantly, phase-amplitude coordinates allow for the study of both the timing and shape of system oscillations. A parallel tool is the infinitesimal shape response curve (iSRC), a variational method that characterizes the shape change of a limit-cycle oscillator under sustained perturbation.

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MS125

Synchronization by Noise for Traveling Pulses

We show synchronization by noise for stochastic partial differential equations which support traveling pulse solutions, such as the FitzHugh-Nagumo equation. We show that any two pulse-like solutions which start from different positions but are forced by the same realization of a multiplicative noise, converge to each other in probability on a time scale $\sigma^{-2} \ll t \ll \exp(\sigma^{-2})$, where σ is the noise amplitude. The noise is assumed to be Gaussian, white in time, colored and periodic in space, and non-degenerate only in the lowest Fourier mode.

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MS125

Convergence of Markov Chains for Constant Step-Size Stochastic Gradient Descent

Stochastic gradient descent (SGD), in the sense of Robbins and Monro 1951, is a popular algorithm for minimizing objective functions that arise in machine learning. Viewing the iterates of SGD as a Markov chain, we show that the associated probability laws converge for separable functions and constant step-sizes (learning rates). In particular, we show that independent of step-size, the state space decomposes into a transient set and a collection of absorbing sets. Each absorbing set is a closed rectangle containing a unique invariant measure, with the set of all invariant measures being the convex hull. Moreover, the set of invariant measures is a global attractor to the Markov chain with a geometric convergence rate. Examples demonstrating the theory include: (1) the failure of the diffusion approximation to characterize the long-time dynamics of SGD; (2) the global minimum of an objective function may lie outside the support of the invariant measures (i.e., even if initialized at the global minimum, SGD iterates will leave); and (3) bifurcations may enable the SGD iterates to transition between two local minima.

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MS126

On Explaining the Surprising Success of Reservoir Computing Forecaster of Chaos and Other Random Neural Network Architectures

Machine learning has become a widely popular and successful paradigm, including for data-driven science. A major application problem is forecasting complex dynamical systems. Artificial neural networks (ANN) have evolved as a clear leading approach, and recurrent neural networks (RNN) are considered to be especially well suited for. In this setting, reservoir computer (RC) has emerged for simplicity and computational advantages. Instead of a fully trained network, an RC trains only read-out weights. However, why and how an RC works at all, despite randomly selected weights is perhaps a surprise. To this end, we offer some simple explanations as to why it works at all, connections to classical methods in time-series forecasting, and operator methods, but also improvements such as our recent next generation reservoir computing formalism (NG-RC) which side steps much of the random aspects but allows for an exactly equivalent but even simpler and more successful approach. Furthermore we for the first time offer some geometric interpretations of another random network.

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MS126

Training Probabilistic Machine Learning Tools to Forecast a Dynamical System from Noisy Observations

Randomization can be used to replace layers of neural networks or kernel matrices of Gaussian processes. This approach accelerates numerical methods and converts training into a least-squares problem. One use case we highlight here is in using random features (a linear combination of randomly drawn shallow neural networks) to replace kernel methods of forecasting of dynamical systems from noisy observations. There is no such thing as a free lunch however, and the necessary hyperparameter optimization of feature distributions, equivalent to the kernel learning problem, becomes more challenging when objective functions are non-deterministic. We present a concrete case study on random features: we create a random loss function jointly inspired from empirical Bayes and cross-validation to learn the feature distribution and propose a suitable algorithm based on ensemble Kalman Inversion (EKI) that can automate its optimization. We demonstrate practical performance when learning 10s or 100s of hyperparameters in several experiments. Due to the black-box treatment of the loss function, and derivative-free nature of EKI, we believe it can be applied widely to improve robustness of tuning other forecasting tools (e.g., reservoir computers), or with other loss functions for learning dynamical systems (e.g., the matching of forecast statistics).

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MS126

Hierarchical Learning of Partially Observed Interrelated Dynamical Systems

We present a novel hierarchical Bayesian inference toolbox that leverages differentiable data-assimilation to learn a set of interconnected, partially observed stochastic dynamical systems. Contrary to the common assumption that each observed data trajectory represents an independent realization of a different (unknown) dynamical system, we study the case where each observed trajectory is unique, yet related to a set of observed, akin trajectories. This set-up underpins many real-world time-series data (e.g., in biomedicine and engineering), as it accommodates the idiosyncrasies of each individual time-series, yet incorporates the similarities across a group of interrelated time-series. Namely, each dynamical system trajectory is idiosyncratic (the individual), yet shares commonalities with other observed trajectories (the population). We merge hierarchical Bayesian modeling with differentiable data-assimilation to efficiently tackle the challenges of filtering, smoothing, predicting, and system identification in these scenarios. We show how the proposed modeling framework and the presented toolbox enables efficient and accurate Bayesian inference of interrelated, linear and/or nonlinear continuous-discrete, partially observed dynamical systems.

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MS126

State-of-the-art Learning of Chaotic Dynamical Systems with Random Feature Maps

Reservoir computers, in particular, echo state networks have long been established as the leading machine leaning architecture for the task of learning and forecasting chaotic dynamical systems from data. Typically the performance of such models are sensitively dependent on several hyperparameters and a lot of effort has been made in the literature to optimize them with minimal computation. In this work we show that a far simpler architecture known as the random feature map and its recurrent, deep and local extensions can be used to achieve state-of-the-art results for learning chaotic systems even in high dimensions. This approach reduces the number of hyperparameters to be optimized to just one. Apart from short-term forecasting, these models are also able to capture long-term behavior of the underlying dynamical system in the test cases. We also show that adding light noise to ill-conditioned training data can drastically improve learning of the corresponding dynamical system.

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MS128

Featurizing Koopman Mode Decomposition with Learned Distances

We introduce Featurized Koopman Mode Decomposition (FKMD), an integrated method for choosing KMD features using a learned Mahalanobis distance on a delay embedded space. The method is inspired by the recent observation that the outerproduct of the weights of a fully trained neural network agree with the average gradient outerproduct (AGOP) of the underlying interpolant (Mechanism for feature learning in neural networks and backpropagation-free machine learning models, Radhakrishnan et al., 2024). The Mahalanobis distance helps with featurizing KMD in cases where good features are not a priori known. We show that FKMD improves predictions for a high-dimensional linear oscillator, a high-dimensional Lorenz attractor that is partially observed, and a cell signaling problem from cancer research.

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MS128

DMD on Hormones

The Hypothalamic-Pituitary-Adrenal (HPA) axis is a major neuroendocrine system, and its dysregulation is implicated in various diseases. This system also presents interesting mathematical challenges for modelling. We consider a nonlinear delay differential equation model and calculate pseudospectra of three different linearizations: a time-dependent Jacobian, linearization around the limit cycle, and dynamic mode decomposition (DMD) analysis of Koopman operators (global linearization). The time-dependent Jacobian provided insight into experimental phenomena, explaining why rats respond differently to perturbations during corticosterone secretion's upward versus downward slopes. We developed new techniques to apply DMD to delay differential equations and we discuss what more we get from the DMD rather than linearizing around the limit cycle. Moving forward, we discuss using DMD to model larger hormonal systems, in particular systems where time series data from hormones may not be availables.

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MS128

Koopman-Based Predictors with Guaranteed Accuracy and Their Application for Control

Extended dynamic mode decomposition (EDMD), embedded in the Koopman framework, is a widely-applied technique for prediction and control of dynamical control systems. However, despite its popularity, the error analysis is still fragmentary. We provide a complete and rigorous error analysis [F. Khne, F.M. Philipp, M. Schaller, A. Schiela, K. Worthmann: L^{∞}-error bounds for approximations of the Koopman operator by kernel extended dynamic mode decomposition, SIAM Journal on Applied Dynamical Systems 2024] for dynamical systems and its extension to control-affine systems [L. Bold, F.M. Philipp, M. Schaller, K. Worthmann: Error bounds and stability of Koopman approximants for control, arXiv preprint 2024]. To this end, we show Koopman invariance of suitably-constructed reproducing kernel Hilbert spaces (RKHS) and leverage approximation-theoretic arguments for (regularised) kernel EDMD. Then, we demonstrate the applicability of the EDMD surrogate models for model predictive control [L. Bold, L. Grne, M. Schaller, K. Worthmann: Data-driven MPC with stability guarantees using extended dynamic mode decomposition. IEEE Transactions on Automatic Control 2024] as well as data-driven controller design of nonlinear systems [R. Strsser, M. Schaller, K. Worthmann, J. Berberich, F. Allgwer; Koopman-based feedback design with stability guarantees. IEEE Transactions on Automatic Control 2024].

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MS128

Remember Me: A Fine-grained Analysis of Input-dependent Mamba Models for Temporal Data

State space models (SSMs) leverage linear time-invariant systems to capture long-range dependencies in temporal data. Mambas, an extension of SSMs, introduce an input-dependent gating mechanism and have emerged as a promising alternative to transformers in language modeling. While Mambas demonstrate strong potential in natural language processing, their selective mechanism imposes an inductive bias that prioritizes memorizing certain inputs over others, which may hinder their ability to model long-range dependencies – a core strength of SSMs. In this talk, we rigorously analyze and compare the selective mechanism in Mambas with traditional SSMs. Our findings highlight potential improvements that enhance Mambas' effectiveness across a broader range of temporal data, paving the way for a more robust and versatile foundational model.

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MS129

Koopmon Trajectories in Nonadiabatic Quantum-Classical Dynamics

The development of numerical methods to simulate fully quantum dynamics, particularly in high-dimensional systems, remains a fundamental challenge in computational mathematics. Standard grid-based methods are generally unfeasible due to the curse of dimensionality and the highly oscillatory nature of quantum wave functions. To alleviate the computational costs, especially in practical applications like quantum chemistry, a common approach is to use mixed quantum-classical (MQC) models, where certain degrees of freedom are approximated classically. However, conventional MQC models often suffer from critical consistency issues, including violations of Heisenbergs uncertainty principle. In response, we recently introduced the *Koopmon* method, a novel MQC approach that combines Koopmans classical mechanics on Hilbert spaces with methods in symplectic geometry. In fact, the Koopmon method arises as a particle closure of an underlying nonlinear continuum PDE model with both variational and Hamiltonian structures, and the computational particles in this model dubbed koopmons sample the Lagrangian classical paths in phase space. In this talk, we introduce the Koopmon method and present numerical experiments proving its effectiveness in achieving results beyond the scope of standard MQC Ehrenfest simulations. Our results cover benchmark models used in nonadiabatic molecular dynamics (Tully models) and extend to recent simulations of momentum coupling for Rashba Hamiltonians.

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MS129

Wave Operators in Physics and Chemistry

In quantum mechanics, the choice of representation profoundly impacts the interpretation and solutions of physical systems. This work introduces and investigates the wave operator representation of quantum dynamics, an approach that uses the square root of the density matrix as its fundamental object. This unique representation not only bridges phase-space and Hilbert-space descriptions of both quantum and classical dynamics but also enhances semiclassical approximations for real and imaginary time evolution, illuminating the transition to the classical limit. Additionally, we present the Wave Operator Minimization (WOM) method for finite-temperature electronic structure calculations. This approach constructs the FermiDirac density matrix by simulating a cooling process from an initially high-temperature state down to the target temperature, preserving physicality at each step via the wave operator formalism. We examine this process for both grand canonical and canonical ensembles, showing that WOM achieves convergence in a fixed number of steps, independent of the system size. This exploration of the wave operator formalism not only opens new avenues in quantum dynamics representation but also revitalizes interest in density matrix minimization techniques for electronic structure and other finite-temperature problems.

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MS129

Machine-learning Interatomic Potentials and Fast Algorithms for Long-range Systems

Machine-learning interatomic potentials have emerged as a revolutionary class of force-field models in molecular simulations, delivering quantum-mechanical accuracy at a fraction of the computational cost and enabling the simulation of large-scale systems over extended timescales. However, they often focus on modeling local environments, neglecting crucial long-range interactions. We propose a Sum-of-Gaussians Neural Network (SOG-Net), a lightweight and versatile framework for integrating long-range interactions into machine learning force field. The SOG-Net employs a latent-variable learning network that seamlessly bridges short-range and long-range components, coupled with an efficient Fourier convolution layer that incorporates long-range effects. By learning sum-of-Gaussian multipliers across different convolution layers, the SOG-Net adaptively captures diverse long-range decay behaviors while maintaining close-to-linear computational complexity during training and simulation via non-uniform FFT. The method is demonstrated effective for a broad range of long-range systems. Additionally, both SOG-Net and classical force fields face scalability challenges due to the limitations imposed by FFT on long-range systems. We will also explore mathematically optimal strategies to replace Ewald-based particle-mesh methods, thereby reducing computational and communication costs.

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MS130

Determination of Stable Branches of Relative Equilibria of the N-Vortex Problem on the Sphere

We consider the N-vortex problem on the sphere assuming that all vorticities have equal strength. We investigate relative equilibria (RE) consisting of n latitudinal rings which are uniformly rotating about the vertical axis with angular velocity ω. Each such ring contains m vortices placed at the vertices of a concentric regular polygon and we allow the presence of additional vortices at the poles. We develop a framework to prove existence and orbital stability of branches of RE of this type parametrised by ω. Such framework is implemented to rigorously determine and prove stability of segments of branches using computer-assisted proofs. This approach circumvents the analytical complexities that arise when the number of rings $n \geq 2$ and allows us to give several new rigorous results. We exemplify our method providing new contributions consisting of the determination of enclosures and proofs of stability of several equilibria and RE for $5 \leq N \leq 12$.

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MS130

Small-Mass Asymptotics of Massive Point Vortex Dynamics in Bose–Einstein Condensates

I will talk about an asymptotic analysis of the massive point vortex dynamics in Bose–Einstein condensates in the small-mass limit $\varepsilon \to 0$. We identify a subspace in the phase space of the massive dynamics—called kinematic subspace $\mathcal{K}$—and show that the orthogonal projection of the massive dynamics to $\mathcal{K}$ yields the standard massless vortex dynamics or the Kirchhoff equations. The main result is a proof that the massive dynamics starting on $\mathcal{K}$ stays $O(\varepsilon)$-close to the massless dynamics for short time. We also perform an asymptotic analysis with a rescaled time to derive the inner approximation to capture the initial layer of the massive dynamics.

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MS130

Point Vortex Dynamics on Surfaces with Continuous Symmetry

Point vortex dynamics (PVD) on surfaces are formally derived from the Euler-Arnold (EA) equation, which is the evolution equation for perfect fluids. Solutions of the EA eq. are geodesic flows for the L^2 energy on the group of volume-preserving diffeomorphisms, but the velocity of PVD flows is not square-integrable. Therefore, it is necessary to mathematically justify that PVD is, in some sense, a solution of the EA eq. We show that PVD is a weak solution of the EA eq. in the sense of de Rham currents. This approach also works when point vortices are advected by a background field, making their evolution equations ODEs with non-local terms involving de Rham currents. Next, we establish surfaces where analytic techniques for PVD are effective. The key device for this is the Killing vector field. Killing vector fields are stationary solutions of the EA eq. and generate isometric actions. Therefore, Killing vector fields are essential for applying the methods of Hamiltonian symmetry to PVD on surfaces, and classifying surfaces that admit them clarifies where such methods apply. From the viewpoint of inflow and outflow, we examine hydrodynamic Killing vector fields, showing that surfaces admitting them are 14 types of Riemann surfaces with rotationally or translationally symmetric conformal metrics. If time permits, we will discuss applications of the above results to PVD.

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MS131

Geostrophic Convection on An Inclined F-Plane

In planetary interiors, stellar interiors, and icy moons' underground oceans, turbulent convection is heavily constrained by rotation, which promotes anisotropy along its axis (the Taylor-Proudman theorem) and the formation of large scale structures via an inverse energy cascade mechanism. The flow morphology and the related transport properties (of heat, momentum, etc.) thus depend crucially on the angle between the rotation axis and local gravity, therefore causing strong variations of the local heat flux with the colatitude in spherical shells. In order to characterize these regional variations, we present a local model, valid in the asymptotic limit of rapid rotation, for quasi-geotrophic Rayleigh-Bnard convection on the tilted f-plane. The influence of both the colatitude and the Rayleigh number Ra are analyzed by performing a computational parametric study. We map out the parameter space by delimiting three regions associated with different morphologies of the large scale barotropic flow: large scale dipolar vortices (LSV, near polar regions), zonal jets (ZJ, near the equator), and bistable states composed of both (at intermediate latitudes and moderate Ra). Concomitantly, we observe that the heat transfer, as measured by the Nusselt number, decreases during the transition from LSV states to ZJ states. This is joint work with Abram Ellison, Keith Julien, Edgar Knobloch, and Michael Calkins.

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MS131

Bridging the Rossby Number Gap in Rapidly Rotating Thermal Convection

Geo-/astrophysical fluid flows are buoyantly driven and strongly constrained at large scales by planetary rotation. Rapidly rotating Rayleigh-Bnard convection (RRRBC) has been studied in experiments and direct numerical simulations (DNS) of such flows, but accessible parameters remain restricted to moderately fast rotation rates (Ekman numbers $Ek10^{-8}$), while realistic astro-/geophysical Ek are much smaller. On the other hand, known reduced equations of motion describing the leading-order behavior in the limit $Ek \to 0$ of rapid rotation do not capture finite rotation strengths, and the most relevant part of parameter space with small but finite Ek remains elusive. Here, using the rescaled incompressible Navier-Stokes equations (RiNSE), a reformulation of the equations of motion based on the limit $Ek \to 0$, to provide full DNS of RRRBC at unprecedented Ek down to $Ek = 10^{-15}$, revealing the disappearance of cyclone-anticyclone asymmetry at $Ek \approx 10^{-9}$. We also find an overshoot in the heat transport as Ek is varied at $\tilde{Ra} = RaEk^{4/3} = const.$, associated with added dissipation by ageostrophic flow. The results confirm boundary layer theory predictions and show that the RiNSE agree with the reduced equations at $Ek \ll 1$. These findings represent a first foray into the vast, largely unexplored parameter space of very rapidly rotating convection. This is joint work with Keith Julien, Benjamin Miquel, Edgar Knobloch and Geoff Vasil.

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MS131

Rotating Rayleigh-Benard Convection: Energetic Consistency, Attractors and Heat Transport Via a Galerkin Hierarchy

Motivated by the need for energetically consistent parameterizations of convective heat transport, in this presentation I will present recent results which develop a mathematically rigorous framework for studying vertical heat transport in turbulent rotating convection. Starting from the paradigmatic Boussinesq-Oberbeck equations with a Coriolis force, heat transport is investigated via the HKC hierarchy of Galerkin truncated ODE models of increasing dimension. The dynamics of these models are studied for varying Rayleigh and rotation numbers, and particular attention is given to stable values of heat transport, as well as the convergence across models where the models accurately represent the PDE. Implications for energetically consistent parameterization of convection will then be discussed.

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MS132

REU in Dynamical Systems at Ithaca College

Our team of three faculty mentors hosted nine undergraduate students at Ithaca College over nine weeks in the summers of 2021-2023. Research teams of three students worked on three different projects in applied dynamical systems. We will discuss the program structure and highlight the team building activities, mentoring, and assessment of the program.

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MS132

Experiences Running a Math and Biology REU

Although a popular scientific discipline at the graduate and research level, mathematics and biology students often have very little overlap as undergraduates. To introduce students to research at the interface of mathematics and biology, an experimental colleague and myself began a REU at Clarkson University that recruited both biological and mathematics students to work on research projects that directly combined both experimental and theoretical components. During the REU, students worked in pairs on mentored research, with one focused on data collection in a laboratory setting and the other focused on computational and mathematical analysis. Each team was mentored by faculty from both the Biology and Mathematics Departments. We ran this REU for three consecutive summers, and during this talk I will discuss my experience both administering and mentoring an REU as an Assistant Professor, as well as give advice for those interested in running truly interdisciplinary research experiences.

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MS132

Building Your REU: Nuts-and-Bolts Insights from a Nonlinear Dynamics Program

TREND is a nonlinear dynamics REU at University of Maryland College Park that has operated continuously since 2003. Over the last 22 years, the program has evolved to its present shape, adapting to the times and implementing lessons learned. In this talk, I will go over the history of TREND and its current moving parts. I will do this with a 'nuts-and-bolts' lens in order to offer detailed, practical insight into building your own REU. Topics I will cover include: recruitment, application logistics, participant selection, on-site participant support, cohort-wide activities, and program assessment.

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MS132

Undergraduate Research in Applied Analysis at West Virginia University

Research Experiences for Undergraduates (REU) programs provide students with valuable hands-on research experience and serve as a pathway to advanced studies. This presentation will share insights from the 2024 REU program in Applied Analysis at West Virginia University, where students worked on a project addressing Systems of Conservation and Balance Laws with Singular Solutions.

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MS133

Oscillatory Mechanisms Governing Insulin Secretion in Pancreatic Beta Cells

Insulin secretion from pancreatic -cells is crucial for regulating the body's glucose homeostasis. Notably, insulin is released in a pulsatile manner, which is believed to be essential for its effective action. At high glucose levels (715 mM), insulin pulses are primarily driven by oscillations in cytosolic free calcium resulting from complex metabolic signaling and ion channels activity, including ATP-sensitive potassium (KATP) channels regulated by the ATP/ADP ratio. Interestingly, oscillations in insulin secretion have also been observed at basal glucose levels (45 mM), when -cells are not electrically active and do not exhibit large calcium oscillations. This suggests another mechanism at play. We propose that intrinsic glycolytic oscillations, which do not require but can be modified by calcium, drive pulses of basal insulin secretion. Data showing oscillations in KATP channel conductance at 3 mM glucose supports this possibility. We test our hypothesis using the Integrated Oscillator Model, which includes two interacting oscillation mechanisms involving intracellular calcium and electrical activity and intrinsic glycolytic oscillations. These mechanisms generate passive (PMOs) and active metabolic oscillations (AMOs), respectively. The model's ability to simulate the transition from AMOs to PMOs as glucose levels rise from basal to high supports our hypothesis, providing a plausible mechanism for oscillations in basal insulin secretion.

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MS133

Golden Oldies and New Dreams from My 30-Year Partnership with Richard Bertram

Insulin is secreted in two phases after a step of glucose from basal to post-prandial levels, a brief 10-minute pulse and a plateau that slowly rises over an hour. These phases are governed by two pools of insulin-containing vesicles, one closely associated with calcium channels at the plasma membrane that can be released as soon as those channels open and mediates the first phase, and one comprising vesicles far away from calcium channels that are released slowly. Both phases of release become progressively impaired as people progress from normal glucose tolerance to pre-diabetes to diabetes, but the first phase has received particular attention, in part because it is easier to measure. The dynamics of calcium are coordinated with these vesicle movements, with an initial pulse of calcium during the first phase and oscillations of calcium during the second phase. Thirty years ago, Bertram, Sherman and their experimental colleagues developed and tested a model for first-phase calcium activity. The initial rise in calcium was attributed to an ion current that is active when the endoplasmic reticulum (ER) is relatively low in calcium and fades as the ER fills in high glucose. The initial tests of the model relied on experimental maneuvers presumed to change the level of ER calcium, but ER calcium could not be measured. Now it can. We will discuss the predictions from modern models of regarding first-phase calcium and how to test them.

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MS133

Dynamic Network Reconfiguration at the Transition Between Rhythmic Motor Programs

The activity of a neural network is shaped by its connectome. However, this structure-function relationship is not fixed and may change dynamically, enabling rapid changes in response to new situations. In frog tadpoles, the motor circuits that generate forward swimming can produce backward-thrusting struggling if the tadpole is held by a predator. Dynamic network reconfiguration between these two rhythms occurs automatically in the spinal cord as sensory inputs change, without involving neuromodulation or feedback from the brain. Whereas swimming involves a wave of muscle contractions propagating from head to tail, struggling is a slower but powerful rhythm that propagates from tail to head. Why does the direction of propagation reverse when the tadpole switches from one motor pattern to another? In this talk I will present mechanisms that can explain how the motor circuits can dynamically change their coordination.

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MS133

Turing's Duckies

We study systems of reaction-diffusion equations in which the diffusivities are widely separated, such as activator/inhibitor systems. We report on the discovery of families of spatially periodic canard solutions that emerge from *singular Turing bifurcations*. The emergence of these spatially periodic canards asymptotically close to the Turing bifurcations is an analog in spatial dynamics of the emergence of limit cycle canards in the canard explosions that occur asymptotically close to Hopf bifurcations in time-dependent ODEs. We show (numerically) that several of the different types of spatial canard patterns are attractors in the PDE. To support the numerics, we use geometric singular perturbation theory to demonstrate the existence of these families of spatially periodic canards. Crucially, in the singular limit, we study a novel class of reversible folded singularities and their bifurcations.

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MS134

Consistency of Graph Signal Processing on Large Networks

The emerging field of Graph Signal Processing (GSP) aims to develop analysis and processing techniques for data that is represented on graphs. Signal analysis on graphs relies heavily on the notion of graph Fourier transform, which is usually defined as the expansion of a signal with respect to an eigenbasis of the associated shift operator. An important question in this field is to develop a common scheme for signal analysis that can be applied to graphs that are similar in structure. The notion of similarity of graphs is beautifully captured by the recent theory of Graph Limit Theory. In this talk, we discuss how defining a graphon Fourier transform allows us to produce consistent graph signal processing for any graph sampled from the graphon. We also briefly discuss GSP on atypical samples of certain graphon using the Large Deviation Principle. This talk is based on collaborative papers with J. Janssen, N. Kalyaniwalla, and G. Medvedev.

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MS134

The Large Deviation Principle for Dynamical Systems on Random Graphs

W-random graphs provide a flexible framework for modeling large random networks. Using the Large Deviation Principle for W-random graphs, we prove the Large Deviation Principle for the corresponding class of random symmetric Hilbert-Schmidt integral operators. Our main result describes how the eigenvalues and the eigenspaces of the integral operator are affected by the large deviations in the underlying random graphon. We discuss implications of this result for dynamical systems on graphs and for graph signal processing. This talk is based on joint work with

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MS134

Searching for Stationary Solutions in Nonlocal Model

This work concerns the challenge of counting steady state solutions to nonlinear PDE known to have multiple stationary states. We propose tackling the problem via a sampling-based approach. We test our proposed methodology on the McKean-Vlasov PDE, which can arise in the continuum limit of interacting particle systems, including Kuramoto models.

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MS135

Expanding on Average Random Dynamics on Surfaces

We consider exponential mixing for volume preserving random dynamical systems on surfaces. Suppose that $(f_1, ..., f_m)$ is a tuple of volume preserving diffeomorphisms of a closed surface M. We now consider the uniform Bernoulli random dynamical system that this tuple generates on M. We assume that this tuple satisfies a condition called being "expanding on average," which means that there exist $C > 0$ and a natural number N such that for all unit tangent vectors $v, E[\ln \|Df^N v\|] > C$, where the expectation is taken over all the realizations of the random dynamics. From this assumption we show quenched exponential mixing. (This is joint work with Dmitry Dolgopyat)

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MS135

Sparsity of Fourier Mass of Passively Advected Scalars in the Batchelor Regime

In this paper we propose a general dynamical mechanism that can lead to the failure of the Batchelor's mode-wise power spectrum law in passive scalar turbulence and hyperbolic dynamics, while the cumulative law remains true. Of technical interest, we also employ a novel method of power spectral variance to establish an exponential radial shell law for the Batchelor power spectrum. An accessible explanation of the power spectrum laws via harmonic analysis is also given. This is joint work with Alex Blumenthal.

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MS135

On regularity of stationary measures for random dynamical systems

I will talk about some results on regularity of stationary measures of random dynamical systems. Under the assumption of absence of almost sure invariant measures, we prove Holder continuity or log-Holder continuity of all stationary measures, depending on estimates for the regularity of random maps. The methods used in the proof also yield interesting results for the non-stationary case. As an application, we prove Central Limit Theorem for non-stationary random products of $SL(2, \mathbb{R})$ matrices. This talk is based on a joint work with Anton Gorodetski and Victor Kleptsyn.

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MS136

Predicting Invasion Speeds Via Marginal Stability and Applications to a Tumor Growth Model

The emergence of complex spatial structures in physical systems often occurs after a simpler background state becomes unstable. Localized fluctuations then grow and spread into the unstable state, forming an invasion front which propagates with a fixed speed and mediates the creation of a new stable state in its wake. The marginal stability conjecture, recently proven for reaction-diffusion systems, asserts that the speed selected in the invasion process is the speed for which the associated front solution is marginally spectrally stable. In this talk, we explain how this conjecture gives a practical criterion for predicting invasion speeds, which can be efficiently verified numerically in large parameter regimes, or analytically near singular limits. We apply this theory to predict invasion speeds in a model for tumor growth driven by cancer stem cells.

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MS136

Quantifying Cell Cycle Regulation by Tissue Crowding

The spatiotemporal coordination and regulation of cell proliferation is fundamental in many aspects of development and tissue maintenance. Cells can adapt their division rates in response to mechanical checkpoints, yet we do not fully understand how cell proliferation regulation impacts collective cell migration phenomena. I will present a suite of continuum models of collective cell migration with cell cycle dynamics, which differ in their ability to describe mechanical constraints and hence cell proliferation regulation. By combining these mathematical models, Bayesian inference, and recent experimental data, I evaluate the level of model complexity that is consistent with the data and quantify the impact of mechanical constraints across different cell cycle stages in epithelial tissue expansion experiments.

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MS136

Front Instabilities in a Reaction-Diffusion Model of Tumor Invasion

We consider planar traveling fronts representing tumor growth in a reaction-nonlinear-diffusion model of tumor invasion. While such fronts are typically stable in one spatial dimension, instabilities can appear in two spatial dimensions when viewing the front as planar interface. Using geometric singular perturbation methods, we describe how the structure of traveling fronts depends on critical system parameter which represents the effect of acid produced by tumor cells on healthy tissue. We also examine the effect on the stability of the resulting interface to perturbations in two spatial dimensions using a combination of asymptotic methods and numerical simulations.

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MS136

The Dynamics of Go Or Grow Tumour Models

In this talk, we will discuss a particular class of mathematical models known as go-or-grow models; these models describe populations where individuals either move or reproduce. Models of go-or-grow type have many applications in biology and medicine, such as the modelling of brain cancer spread. The analysis of these models has inspired new mathematics, and this talk aims to discuss the mathematical properties of go-or-grow models of reaction-diffusion type. We are focusing on results on pattern formation, critical domain size problems, and travelling waves. We were able to develop new general results on the critical domain size problem and the travelling wave problem. Moreover, we follow the arguments of Marciniak-Czochra, among others, which show a high level of instability of the go-or-grow models, which can lead to high-frequency instabilities.

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MS137

Dynamical Systems Cost-fitting Landscape: A New Method for Clustering Longitudinal Gene Expression in Sepsis Progression

Sepsis is a severe inflammatory response to infection possibly leading to organ dysfunction and death. Effective treatment is challenging due to its clinical heterogeneity and complex progression dynamics. Traditional sepsis research often focuses on static gene expression profiles which overlook temporal changes in gene expression that may reveal critical insights into disease progression. This study introduces a novel trajectory clustering method, the Dynamical Systems Cost-fitting Landscape (DSCL), designed to identify clusters of gene expression trajectories, called dynamic endotypes, in sepsis patients utilizing dynamical systems. Using data from 573 blood samples from a Ghanaian sepsis cohort, the DSCL method models gene expression trajectories phenomenologically with ODEs, measures trajectory similarities based on cost-fitting, and applies multi-layer bundling (MLB) clustering to uncover distinct dynamic endotypes. This dynamic endotyping approach reveals different trajectories of recovery and non-recovery among sepsis patients, suggesting varied paths to mortality and potential for personalized treatment. This framework extends beyond sepsis, offering a powerful tool for studying gene expression dynamics in other diseases, such as cancer or autoimmune disorders, characterized by temporal host body immune response.

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MS137

On the Loss of Synchronization in a Gap Junctionally Coupled Network

Synchronization of beta cells within pancreatic islets are known to occur and to be useful for pulsatile secretion of insulin. Disruption in synchronization has been linked to the onset of diabetes. Heterogeneity in cellular parameters from excitability to metabolism have been identified in subpopulations of beta cells. We have extended previous results on coupled excitable cells in undirected networks to coupled bursters to obtain conditions for synchronization of bursting cells clustered in subpopulations using semi-passivity and a non-smooth Lyapunov function. This work is presented in honor of Richard Bertram's 60th Birthday!

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MS137

Using a Dynamic Threshold Curve to Study Neuronal Phase-Locking

Medial superior olive (MSO) neurons in the mammalian brain stem are excitable units that achieve sound localization by producing spikes at temporally precise phases relative to the periodic sensory signals that drive them, despite jitter in the arrival times of these signals and cycle skipping. Past work has shown numerically that the extent of this response precision depends on the computational MSO model that is simulated. In this work, we use a dynamical systems perspective to analyze the features that determine this outcome and the timing of the spikes produced. Specifically, we build from earlier ideas relating to what was called a quasi-threshold separatrix, and from our own previous study of the sensitivity of spiking to the slope of an applied input current, by introducing a related but distinct concept that we call the dynamic threshold curve (DTC). We analyze how the properties of an excitable neuron model and its periodic forcing shape the DTC and how the DTC determines when, and with what precision, model spikes will occur.

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MS137

A Nonstandard Geometric Singular Perturbation Analysis of the Active Metabolic Oscillatory Subsystem in Pancreatic Beta Cells

Insulin secretion by pancreatic beta cells in response to blood sugar level is fundamental to vital life functions, and is modulated by the tight bidirectional coupling of electrical and metabolic oscillators. This talk focuses on the Active Metabolic Oscillator (AMO) sub-module of the Integrator Oscillator Model (IOM) for pancreatic beta-cells (e.g., Bertram et al, 2023). We non-dimensionalize the model to identify small parameters and processes evolving on multiple different timescales. We proceed to identify the oscillatory regime of this model and show that such metabolic oscillations can be recast as relaxation oscillations. Using the coordinate-independent geometric singular perturbation theory toolbox (e.g., Kosziuk & Szmolyan 2011; Wechselberger, 2020), we rigorously explain the observed metabolic oscillations. In particular, we use the parametrization method (e.g., Lizarraga et al., 2021) and the blow-up method (e.g., Dumortier 1993) to construct the AMO cycle. We would like to thank Richard Bertram and Patrick Fletcher for stimulating discussions regarding the IOM and, in particular, the AMO.

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MS138

Variability in a Single-Hemisphere Box Model for the Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is a large-scale ocean circulation system spanning the entire Atlantic Ocean, driven by salinity and temperature gradients between lower and higher latitudes. Substantial evidence indicates that the AMOC has weakened over the last century and that increased freshwater influx into the North Atlantic may result in abrupt changes in its overturning strength. We propose a conceptual single-hemisphere box model that divides the ocean into three distinct compartments: an equatorial box, a subpolar surface box, and a substantially larger deep-water box beneath them. Bifurcation analysis reveals bistability between steady states and self-sustaining oscillations between weaker and stronger overturning states. Additionally, we demonstrate that for intermediate values of freshwater influx, the model exhibits chaotic dynamics emerging through a period-doubling cascade and boundary crisis.

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MS138

Resonant Dynamic B-Tipping Close to a Non-Smooth Saddle-Focus Bifurcation Linked to Climate Change

We study the behaviour of (resonant) dynamic B-tipping in a forced two-dimensional non-autonomous system close to a non-smooth saddle-focus (NSF) bifurcation. The NSF arises when a saddle-point and a focus meet at a border collision bifurcation. The emphasis is on the Stommel 2-box model, which is a piecewise-smooth continuous dynamical system, modelling thermohaline circulation. This model exhibits a NSF as parameters vary. By using techniques from the theory of non-smooth dynamical systems we are able to provide precise estimates for the general tipping behaviour close to the NSF as parameters vary. In particular we consider the combination of both slow drift and also periodic changes in the parameters, corresponding, for example, to the effects of climate change and seasonal variations. The results are significantly different from the usual B-tipping point estimates close to a saddle-node bifurcation. In particular we see a more rapid rate of tipping in the slow drift case, and an advancing of the tipping point under periodic changes. The latter is made much more pronounced when the periodic variation resonates with the natural frequency of the focus, leading both to much more complicated behaviour close to tipping, and also significantly advanced tipping in this case.

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MS138

Transitional States During Compound Extreme Events: Examples from Cascading Wildfires and Floods

Wildfires and floods are examples of compound extreme weather events that have broad societal implications. While each event can be damaging on its own, their interactions can lead to cascading effects. For example, wildfires can impede soils ability to absorb water, which can lead to increased stormwater runoff from heavy precipitation and thus more severe flooding. In this talk, we use the western United States as an exemplar to evaluate transitional states between individual extreme events that contribute to compound events. To do so, we utilize a probabilistic model based on Markov modeling to estimate transition probabilities based on historical climate data. This enables us to capture the dynamics of underlying interactions between climate variables. Our findings contribute towards better predictive modeling of extreme weather to support coupled human-natural system resilience.

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MS138

Predictor Sensitivity and Variable Importance in Drought Forecasting

Reservoir networks are a type of recurrent neural network useful in modeling complex behavior due to their rich internal dynamics. Such networks are even capable of forecasting chaotic systems and can be utilized as a black box model for drought. While useful for standard prediction, the black box nature can make other analysis challenging or intractable. In this talk, we explore the potential for reservoir networks to inform conceptual model design. We train a reservoir network to predict the outcome of the Vano system a system of four equations exhibiting chaotic behavior. We then apply the Shapley additive explanation values analysis to the inputs and outputs of the trained network to determine which input variables are most sensitive to the change in prediction. Though the Shapley analysis is not new to feature analysis, the method must be adapted for the nuances of the time series and trajectory-dependent data present in the Vano system and drought data. For comparison, we also consider other methods of variable importance analysis for the trained reservoir network. Looking forward, we provide a use case in drought prediction, discussing how those most sensitive inputs could validate or improve conceptual drought models through variable selection. SAND2024-13905O.

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MS139

Modeling Tandem Running Dynamics: Contact-Based Pair Coordination in Collective Motion

We introduce a tandem running model to capture the intricate dynamics of coordinated pair movement, drawing inspiration from termite behavior. The model replicates the nuanced interplay between partners during tandem runs, where one individual leads while the other follows, or both move in a synchronized manner. By analyzing the trajectories of termite pairs, we explore how the dynamics evolve under varying leader-follower roles and levels of coordination, including transitions between independent movement, stable tandems, and transient swarming. Empirical validation is conducted using termite species with distinct tandem stability and leader roles, providing a foundation for understanding pair-based movement strategies. The model is further applied to develop autonomous systems capable of tandem runs, showcasing its potential for advancing collective behavior research and robotics. This work emphasizes the dynamics of paired interactions as a cornerstone for studying and engineering coordinated movement in both biological and artificial systems.

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MS139

Classification and Coordination in Collectives: Lessons from Ants for Building Self-Organized Systems in Physical Space

We will discuss how distributed systems, such as multi-robot systems, have to deal with interference from others, and this talk will discuss methods derived from ants for using the physical environment (both in terms of the ants and the environment around the ants) as dynamic information source that provides the possibility that "cognitive collectives" have externalized mental states, fully separating some aspects of the "mind" from the body.

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MS139

Emergent Spatiotemporal Patterns in Insect Swarms

For the overwhelming majority of organisms, effective communication is critical in the quest to survive and reproduce. A better understanding of these communication signals and how they evolved can benefit from physics, mathematics, and computer science via the application of concepts like energetic cost, compression (minimization of bits to represent information), and detectability (high signal-to-noise-ratio). My lab's goal is to formulate and test phenomenological theories about natural signal design principles and their emergent spatiotemporal patterns. To that end, we adopted insect swarms as a model system for identifying how organisms harness the dynamics of communication signals, perform spatiotemporal integration of these signals, and propagate those signals to neighboring organisms. In this talk, I will focus on two types of communication in insect swarms: visual communication, in which fireflies communicate over long distances using light signals, and chemical communication, in which bees serve as signal amplifiers to propagate pheromone-based information about the queen's location. Through a combination of behavioral assays and computational techniques, we develop and test model-driven hypotheses to gain a deeper understanding of these communication processes and contribute to the broader understanding of animal communication.

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MS140

Solitary Waves in Fermi-Pasta-Ulam-Tsingou Lattices with Long Range Particle Interaction

We study the existence and properties of certain kind of traveling waves (nearsonic solitary waves) in Fermi-Pasta-Ulam-Tsingou (FPUT) Lattices. These are infinite, one dimensional chains of identical particles arranged on a horizontal line with infinite nonlocal particle neighbors interactions on both sides. We consider both next neighbor particle interactions and long range particle interactions. In both cases, we prove the existence of localized traveling waves which relies on the Implicit Function Theorem. Techniques of Fourier analysis enable us to reformulate the problem to the study of waves that are small perturbations of well known ODEs. Additionally, we deploy the method originally developed by Beale for a capillary water wave problem to prove the existence of nanopterons solutions. The nanopteron wave profiles are formed by the superposition of an exponentially decaying term (a small perturbation of a KdV ^{2} -type soliton) and a periodic term with a very small amplitude. The solution develops a ripple as $|x| \to \infty$. The periodic wave solution is an essential part of our analysis.

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MS140

Existence and Stability of Rogue Waves in Discrete Models

This talk will focus on the formation of rogue waves, in the form of time-periodic and spatially localized solutions known as Kuznetsov-Ma (KM) breathers in the discrete, focusing nonlinear Schrödinger (DNLS) equation and Ablowitz-Ladik (AL) systems. In doing so, we will investigate the existence, stability and dynamics of KM breathers in the Salerno model which itself interpolates between the DNLS and AL systems. We will explore the configuration space of KM breathers by varying the homotopy parameter associated with the Salerno model (connecting the AL and DNLS models) as well as the period of the solution. We will show that on one hand, the KM breather in the AL model is not the only one solution since more KM solutions bearing oscillatory tails are shown to be present therein. On the other hand, and as per the DNLS model, novel KM breathers will be presented in this case. Then, upon using a proximity argument, KM breathers on a flat background will be shown to exist for the DNLS case. The results will be complemented by discussing the stability of the solutions using Floquet theory and direct dynamical simulations. More recent results on the defocusing AL system will be presented too (if time permits) and open problems and questions will be discussed.

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MS140

Periodic Traveling Waves in Dimer Fermi-Pasta-Ulam-Tsingou Lattices Without Symmetry

We prove the existence of small-amplitude periodic traveling waves in dimer Fermi-Pasta- Ulam-Tsingou (FPUT) lattices without assumptions of physical symmetry. Such lattices are infinite, one- dimensional chains of coupled harmonic oscillators in which the oscillator masses and/or the coupling potentials can alternate. Previously, periodic traveling waves were constructed in a variety of limiting regimes for the symmetric mass and spring dimers, in which only one kind of material data alternates. The new results discussed here remove the symmetry assumptions by exploiting the gradient structure and translation invariance of the traveling wave problem. Together, these features eliminate certain solvability conditions that symmetry would otherwise manage.

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MS141

Characterizing Dynamical Stability of Stochastic Gradient Descent in Overparameterized Learning

For overparameterized optimization tasks, such as the ones found in modern machine learning, global minima are generally not unique. In order to understand generalization in these settings, it is vital to study to which minimum an optimization algorithm converges. The possibility of having minima that are unstable under the dynamics imposed by the optimization algorithm limits the potential minima that the algorithm can find. I will present our work where we characterize the global minima that are dynamically stable/unstable for both deterministic and stochastic gradient descent (SGD). In particular, we introduce a characteristic Lyapunov exponent which depends on the local dynamics around a global minimum and rigorously prove that the sign of this Lyapunov exponent determines whether SGD can accumulate at the respective global minimum.

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MS141

A Localized Schroedinger Bridge Sampler for Generative Modelling

We consider the generative problem of sampling from an unknown distribution for which only a sufficiently large number of training samples are available. We show how combining Schroedinger bridges and Langevin dynamics provides an efficient framework for such problems, in particular for data which are concentrated on a compact submanifold. A key bottleneck of this approach though is the exponential dependence of the required training samples on the dimension d of the ambient state space. We propose a localization strategy which exploits conditional independence of conditional expectation values. Our localization replaces a single high-dimensional Schroedinger bridge problem by d low-dimensional Schroedinger bridge problems over the available training samples. In this context, a connection to multi-head self attention transformer architectures is established. The localized sampler is stable and geometric ergodic. The sampler also naturally extends to conditional sampling and to Bayesian inference. We demonstrate the performance of our proposed scheme through experiments on a Gaussian problem with increasing dimensions, on a temporal stochastic process, and on a stochastic subgrid-scale parametrization conditional sampling problem.

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MS141

Diffusion Generative Modeling in Non-Euclidean Spaces

Machine learning in non-Euclidean spaces have been rapidly attracting attention in recent years, and this talk will give some examples of progress on its mathematical and algorithmic foundations. A sequence of developments that eventually leads to non-Euclidean generative modeling will be reported. More precisely, I will begin with variational optimization, which, together with delicate interplays between continuous- and discrete-time dynamics, enables the construction of momentum-accelerated algorithms that optimize functions defined on manifolds. Selected applications, namely a generic improvement of Transformer, and a low-dim. approximation of high-dim. optimal transport distance, will be described. Then I will turn the optimization dynamics into an algorithm that samples from probability distributions on Lie groups. This sampler provably converges, even without log-concavity condition or its common relaxations. Finally, I will describe how this sampler can lead to a structurally-pleasant diffusion generative model that allows users to, given training data that follow any latent statistical distribution on a Lie group, generate more data exactly on the same manifold that follow the same distribution. If time permits, applications such as molecule design and generative innovation of quantum processes will be briefly discussed.

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MS141

Theoretical Implications of Training and Sampling Diffusion Models

Most existing theoretical investigations of the accuracy of diffusion models, albeit significant, assume the score function has been approximated to a certain accuracy, and then use this a priori bound to control the error of generation. In this talk, I will show a quantitative understanding of the whole generation process, i.e., both training and sampling. More precisely, it conducts a non-asymptotic convergence analysis of denoising score matching under gradient descent. In addition, a refined sampling error analysis for variance exploding models is also provided. The combination of these two results yields a full error analysis, which elucidates (again, but this time theoretically) how to design the training and sampling processes for effective generation. For instance, our theory implies a preference toward noise distribution and loss weighting in training that qualitatively agree with the ones used in Karras et al. 2022. It also provides perspectives on the choices of time and variance schedules in sampling: when the score is well trained, the design in Song et al. 2021 is more preferable, but when it is less trained, the design in Karras et al. 2022 becomes more preferable.

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MS142

Modulation of Synchronization by Acetylcholine

Synchronized activity of neurons is important for many aspects of brain function. Synchronization is affected by both network-level parameters, such as connectivity between neurons, and neuron-level parameters, such as firing rate. At the neuron-level, we consider the neurotransmitter acetylcholine, which has been shown to modulate the firing properties of several types of neurons through the down-regulation of voltage dependent potassium currents such as the muscarine-sensitive M-current. We will show how the M-current affects the bifurcation structure of a generic conductance-based neural model and how this determines excitability properties of the model. We then use phase-model analysis to study the interplay between the effect of the M-current on neural excitability and the effect of the connectivity structure of the network on the existence and stability of phase-locked solutions.

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MS142

Comodulation of Neurotransmitters in the Brain and Their Implications for Neurophysiology

In volume transmission, or neuromodulation, neurons communicate not through direct, one-to-one synaptic connections, but by releasing neurotransmitters broadly into the extracellular space from numerous varicosities. Often, the cell bodies are located in one brain region, while their axons extend to distant areas, diffusing neurotransmitters over a wider network. In the first part of my talk, I will present recent findings on the comodulation of histamine and serotonin through a mathematical model that encompasses neurotransmitter synthesis, reuptake, removal, and release into the extracellular space. In the second part, I will explore the regulatory role of the sex hormone estrogen on these systems, showing how it can influence neurotransmitter dynamics and lead to distinct responses in male and female neuronal systems. This analysis provides insight into sex-specific differences in neuromodulatory systems, which could have broader implications for understanding sex differences in brain function and disease.

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MS142

Modulation of Respiratory Neuronal Dynamics: Insights from Norepinephrine

Respiration is an essential involuntary function necessary for all living beings to survive. The preBötzinger complex (preBötC) network in the mammalian brainstem is a neuronal network that drives the inspiratory phase of the respiratory rhythm. In isolation in vitro, this neural network is rhythmically active and has been experimentally shown to be constantly modulated by numerous neuromodulators through altering properties of the network. In this work, we investigate the effects of modulating certain model parameters influenced by Norepinephrine (NE) on respiratory dynamics via a focus on the preBötC. Our model successfully reproduces certain differential effects of NE on preBötC dynamics noted experimentally, while also offering some other novel predictions. In particular, we explore interesting mixed bursting dynamics obtained as a model response to studying the effects of NE. Through our modeling approach and methods of dynamical systems theory, we uncover the mechanisms through which NE differentially modulates different types of preBötC neurons, providing insights into its overall impact on the network properties.

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MS142

Cholinergic Modulation of Network Dynamics and Memory Consolidation

Acetylcholine (ACh) is a potent neuromodulator that is typically high during active behavior and low during inactive states. It critically influences network dynamics via various synaptic and cellular mechanisms. We developed in silico modeling framework to investigate how ACh affects information storage in the network via modulation of network-wide excitatory/inhibitory (E/I) balance during afore mentioned vigilance states. Specifically, we simulate a spatio-temporal memory as complex target (reward) search during which (imaginary) subject traverses a maze composed of multiple junctions, represented spatially by activation of a network of excitatory and inhibitory neurons. We show that changes in ACh levels afect the network-wide E/I balance driving distinct activation patterns in the network. Namely, high ACh concentrations, associated with active behavior, activate only local neuronal representations that code for spatially and temporally confined features of the memory. In contrast low ACh concentrations, associated with resting state, synchronously reactivate long-range search paths representing temporally extended memory trace. This differential activation and subsequent consolidation of different memory features via spike timing dependent plasticity (STDP) allows for extrapolation of spatio-temporally confined memory features into coherent memory of the traversed trajectory.

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MS143

Integral-form Sparse Model Selection for Stochastic Differential Equations

Sparse regression methods for nonlinear system identification received significant attention in recent years. These methods are seen as especially promising for scientific machine learning applications, where the goal is to learn an interpretable dynamic model from a time series of experimental observations. Popular methods including SINDy and weak-form sparse identification address the case where the observed process is deterministic, i.e. can be described as a noisy observation of a system of ordinary or partial differential equations. However, many systems of scientific interest, including many biological systems, have significant process noise and are better described with stochastic differential equation models. In this talk we present a new sparse regression-based system identification approach that allows for the simultaneous learning of nonlinear drift and diffusion terms in stochastic differential equations from data, leveraging classic identities from Ito calculus. Analogously to weak-form methods for deterministic systems, our new method involves numerical integration of stochastic signals against user-defined test functions. We illustrate the effectiveness of our approach on benchmark examples and discuss open questions.

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MS143

Recent Advances in Weak-Form System Identification: Hidden Variables and Biological Digital Twins

Recent advances in data-driven modeling approaches have proven highly successful in a wide range of fields in science and engineering. Via learning governing equations, they offer an explainable scientific machine-learning framework that serves as a foundational building block for digital twins. However, the first generation of these methods has proven poorly suited to the noise-corrupted data commonly encountered in biological systems. In this talk, I will describe our equation learning (WSINDy) and parameter estimation (WENDy) algorithms, which address several challenges within conventional model development and inference in mathematical biology. A notable problem in using our weak-form approach to build biological digital twins is how to address unobserved variables. In this work, we will demonstrate how WENDy, combined with an elimination algorithm from differential algebra, leads to an efficient, accurate, and robust approach for creating twins.

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MS143

Physiological Models of Thermoregulation Across Species

Many organisms use heterothermy, or the ability to switch between homeothermy (a constant, regulated body temperature) and poikilothermy (a dramatically varying body temperature), as an energy optimization and survival strategy. The Arctic ground squirrel (AGS) uses different thermoregulatory strategies throughout the year. In the summer, the AGSs body temperature remains relatively constant at about 37 degrees C. During the winter hibernation, the AGS exhibits extreme body temperature spikes of nearly 40 degrees C in amplitude, resembling a deterministic excitable bistable system. It is currently unknown what physiological process drives body temperature spiking during hibernation in the AGS, but two mechanistic hypotheses have been proposed. The first hypothesis suggests that the spiking is driven by a non-temperature-compensated circadian clock. The second hypothesis suggests that spiking is driven by a threshold on a (currently unknown) metabolite. Using data-driven techniques, we find a physiological model that lends support to the second hypothesis. Additionally, we use time delay embedding on body temperature time series collected across organisms, and we find the dimensionality of the underlying system is low. We show that the AGS model (modified to incorporate environmental signals) can recapitulate body temperature patterns across organisms. These results suggest that there may exist a universal thermoregulatory mechanism across heterothermic species.

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MS143

Multi-Objective Sindy for Parameterized Model Discovery from Single Transient Trajectory Data

The sparse identification of nonlinear dynamics (SINDy) has been established as an effective technique to produce interpretable models of dynamical systems from time-resolved state data via sparse regression. However, to model parameterized systems, SINDy requires data from transient trajectories for various parameter values over the range of interest, which are typically difficult to acquire experimentally. In this work, we extend SINDy to be able to leverage data on fixed points, limit cycles, quasiperiodic orbits and/or chaotic attractors to reduce the number of transient trajectories needed for successful system identification. To achieve this, we incorporate the data on these attractors at various parameter values as constraints in the optimization problem. First, we show that enforcing these as hard constraints leads to an ill-conditioned regression problem due to the large number of constraints. Instead, we implement soft constraints by modifying the cost function to be minimized. This leads to the formulation of a multi-objective sparse regression problem where we simultaneously seek to minimize the error of the fit to the transients trajectories and to the data on attractors, while penalizing the number of terms in the model. Our extension, demonstrated on several numerical examples, is more robust to noisy measurements and requires substantially less training data than the original SINDy method to correctly identify a parameterized dynamical system.

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MS144

Spatial Patterns in Population Aggregation

We study the roles of competition, motility, and altruism in population aggregation. We find that these factors, when balanced appropriately, lead to spatial patterning, both in an agent-based and mean-field formulation. We prove the existence of spatial patterns near onset in the mean-field formulation, and show agreement numerically between the mean-field and agent-based problems. We also study weak convergence of the agent-based model to a mean-field model in the large-population limit. Ongoing questions include more complex spatial patterns in two dimensions and whether mutation can lead to natural selection towards altruistic traits.

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MS144

PDE Models of Cross-Scale Evolutionary Dynamics in Group-Structured Populations

Natural selection often operates simultaneously across multiple levels of biological, with evolutionary tensions often arising between traits or behaviors that are favored at different levels of selection. One common example of this tension arises in the evolution of altruism in group-structured populations, in which actions that are costly and result in an individual-level disadvantage while providing a collective benefit to the individuals group. In this talk, we will explore a variety of PDE models that use evolutionary game theory to describe the evolution of altruism under competition occur both within and among groups, and we will discuss how different formulations of individual-level and group-level birth and death events can impact the long-time support for cooperation under these PDE models.

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MS144

Virulence Versus Transmission in An Evolutionary Disease Model

In this talk I will describe recent work on the interplay between virulence, transmissibility, and evolution in a ”spatial” SIR model. Evolution is here described by diffusion along a one-dimensional phenotype space, while the remaining population-level dynamics such as births, deaths, infection, and recovery are governed by appropriate spatial modifications of standard SIR-type kinetics. The resulting model takes the form of a system of integro-differential equations for which we can use a combination of asymptotic and numerical methods to qualitatively explore the role of virulence and transmissibility on viral dynamics.

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MS144

Temporal Variability Can Promote Migration Between Habitats

Understanding the conditions that promote the evolution of migration is important in ecology and evolution. When environments are fixed and there is one most favorable site, migration to other sites lowers overall growth rate and is not favored. Here we ask, can environmental variability favor migration when there is one best site on average? Previous work suggests that the answer is yes, but a general and precise answer remained elusive. Here we establish new, rigorous inequalities to show how stochastic growth rate can increase with migration when fitness (dis)advantages fluctuate over time across sites. The effect of migration between sites on the overall stochastic growth rate depends on the difference in expected growth rates and the variance of the fluctuating difference in growth rates. When fluctuations are large, a population can benefit from bursts of higher growth in sites that are worse on average. Such bursts become more probable as the between-site variance increases. Our results apply to many (= 2) sites, and reveal an interplay between the length of paths between sites, the average differences in site-specific growth rates, and the size of fluctuations. Our findings have implications for evolutionary biology as they provide conditions for departure from the reduction principle, and for ecological dynamics: even when there are superior sites in a sea of poor habitats, variability and habitat quality across space determine the importance of migration.

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MS145

Math + AI + Wearables for Sleep and Mood Disorders

We are in the era of “Medical Big Data,” driven by advancements in experimental and medical techniques. In this talk, I will illustrate how the combination of machine learning and mathematical modeling can be leveraged to analyze big data, yielding valuable insights for more accurate and efficient diagnosis and treatment with focus on sleep disorders. First, I will demonstrate how mathematical modeling and machine learning techniques can be used to dissect the complex sleep patterns of shift workers and individuals with mood disorders, as measured by wearable devices. This innovative approach allows us to identify personalized sleep-wake patterns that effectively minimize daytime sleepiness and mood disorders. This research has led to the development of the mobile application “SleepWake,” which provides individuals with tailored sleep schedules, optimizing their overall sleep experience.

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MS145

Mathematical Modeling Hormonal Interactions in

Women

During the fertile life-span, the ovulatory-menstrual cycle is a regulatory process in women, producing sex hormones in the ovaries (i.e. estradiol, progesterone, testosterone). These hormones set the cyclic pattern of 26-35 days in females, which is not only relevant regarding fertility. Increasing scientific research shows how the ovulatory menstrual cycle supports women's health, impacting systemically the female body. Changes along the ovulatory menstrual cycle and throughout women's life also modify the dynamics in important subsystems such as the metabolic and the cardiovascular one. In the same spirit, disruptions in menstrual cycles also alter other systems and increase the risk for diseases. For example, hormonal changes that occur during menopause lead to an increased risk for cardiometabolic diseases. In this talk, I will present mathematical models describing systemic interactions and results from simulations of the ovulatory menstrual cycle impacting other subsystems in health and disease. Also, I will show how these particular mathematical models serve as a tool to generate hypotheses and get unknown insights on complex, highly interactive phenomena and their underlying mechanisms.

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MS145

Health Change Detection by Comparison of Dynamic, High Dimensional, Complex Systems

Machine learning algorithms struggle in health applications, often causing harmful biases against specific populations in place of random errors. This is in large part for two reasons. First, variance in biological systems is not gaussian random, but highly structured in time as a result of numerous non-linear feedback loops providing tunable autoregulation to the system (i.e. circadian rhythms, hormone pulses, etc.). The second is that biological systems are complex, behaving like strange attractors in many ways, due to the complexity of the regulation involved, and the unpredictability of the environment affecting the exact manifestations of the various feedback components within the system. Any systematic differences in parameters for quasi-rhythmic or complex behaviors will create non-random differences in the statistics of measurement data, resulting in algorithm biases. Since the most well measured population in western medicine in white middle-aged males, biases tend to be against women and other ethnicities, exacerbating health disparities. In this talk we present methods of estimating relationships between individuals using statistical, time series, and machine learning methods. We explore the relationship between statistical features from biological signals, and parameterization of dynamical systems. The result is novel approaches to phenotyping individuals, and insights into the limit function of algorithmic accuracy.

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MS146

Quantile Conserving Ensemble Filters for Non-Gaussian and Nonlinear Data Assimilation

Ensemble filter assimilation algorithms can be described as two steps: 1). Computing increments for an observed variable given an ensemble prior and an observation; 2). Computing increments for state variables given the observation increments. An efficient algorithm that allows the use of arbitrary continuous priors and likelihoods for the first step is described. The key innovation is to select posterior ensemble members with the same quantiles with respect to the continuous posterior distribution as the prior ensemble had with respect to the prior continuous distribution. The second step is a regression in a space to which observed and state variables are independently transformed with a probability integral transform followed by a probit transform; this is a specific form of anamorphosis. This guarantees that the posterior ensembles for state variables have many of the advantages of the observation space quantile conserving posteriors. For example, if state variables are bounded then posterior ensembles will respect those bounds and eliminate most bias near the boundary. The new method is applied to an idealized chaotic tracer transport problem where it is shown to have significant advantages compared to traditional linear-Gaussian ensemble filters.

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MS146

A Hybrid Controlled Particle Filter for Chaotic Systems with Sparse Observations

Particle filters provide a general and flexible approach to numerically approximate the nonlinear filtering solution but suffer from particle degeneracy, which is amplified in high-dimensional, chaotic, and sparsely observed systems. Data assimilation for many geophysical problems, such as atmospheric, oceanic or space weather related systems have these properties. Optimal control based approaches have been suggested to mitigate particle collapse; either by introducing control between observations to provide samples from an optimal proposal, or to introduce a control during an artificial timespan to flow particles from prior to posterior as a continuous-time solution to Bayes' formula. Each approach has various advantages and disadvantages. In this talk we introduce a hybrid approach that attempts to blend the best of both methods, providing samples approximating those from an optimal proposal and improving the numerics for the Bayesian flow method. Analysis and comparison results of the hybrid approach to the aforementioned controls-based particle filtering and standard data assimilation methods is made on chaotic atmospheric testbed problems by Lorenz.

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MS146

A Computable Distribution for Filter Weights in

Data Assimilation

Weighted algorithms - meaning Particle Filters and Gaussian sum filters - are a ubiquitous topic in the sciences. These filters have attractive theoretical properties and easily fuse dynamical models and data in order to learn parameters and track state variables; but they also have a degeneracy problem in high-dimensional inference. Twenty years of research in Data Assimilation has produced many tweaks and improvements on the Particle Filter. However, to the best of my knowledge, there is only limited understanding of the cause of degeneracy - in asymptotic regimes, for example. I will present, under mild assumptions, a probability distribution function for the weights of any weighted algorithm for data whose measurement error is Gaussian. The distribution of the weights depends on two scalars only. I will sketch two powerful use cases. The first use case is straightforward: one can *anticipate* the performance of a weighted algorithm on a complex problem or one can *predict* which of many weighted algorithms would be the least degenerate, and so on. The second use case may radically improve the utility of weighted algorithms: rather than setting hyper-parameters in the weighted algorithm, I propose to select them at the exact moment when a weighted algorithm would compute weights—by computing the two scalars that govern the weights and then selecting the hyper-parameters so as to avoid degeneracy in the weighted algorithm.

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MS146

Unbiased Nonlinear Data Assimilation for Turbulent Geophysical Flows Combining Particle Flow Filters and Diffusive Methods

Recently, many new fully nonlinear data-assimilation methods have been developed in the data-assimilation, mathematical, statistical, and machine learning communities that can be applied to high-dimensional systems. Of particular interest are so-called particle flow filters and diffusion-based filters because of their efficiency, making them computationally compatible with standard data-assimilation methods such as Ensemble of 3D- or 4DVars. Stochastic Particle Flow filters minimize the distance between a set of particles and the posterior pdf in an iterative way, and are unbiased even for finite ensemble sizes. However, they rely on accurately estimating the gradient of the logarithm of the prior, which can be hard from a set of prior particles. Diffusion-based methods are quickly becoming mainstream in machine learning as methods to generate samples from highly non-Gaussian densities using Langevin dynamics, and, with a small addition, turn out to have great potential in data assimilation. Interestingly, these diffusion-based methodsdo not need the gradient of the logarithm of the prior for their performance. In this presentation I will explain how these methods are connected and how we can make them useful for high-dimensional problems using examples from geophysical turbulence, and how the superior developments in traditional data assimilation can considerably accelerate some of these methods.

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MS147

Fluctuation-dependent Consumer Coexistence: Testing the Robustness of Relative Non-linearity in More Realistic Food Web Modules

The remarkable biodiversity observed in natural ecosystems continues to challenge ecological theory. Mechanisms of species coexistence operate under either constant or temporally variable environmental conditions. A well-known example of a fluctuation-dependent mechanism, the gleaneropportunist trade-off, operates through differences in species' resource-dependent growth rates: the gleaner performs better at low, the opportunist at high resource densities. The curvatures of the species functional responses also impact the stability of the underlying consumerresource dynamics differently: the opportunist stabilizes, while the gleaner destabilizes population dynamics. The classical example that serves as a baseline model for this relative non-linearity of competition is the exploitative competition between two consumers that exhibit different, i.e. linear and saturating, functional responses. While this clearly demonstrates the core mechanism, it is limited in scope. Here, we extend this model by introducing a shared predator and incorporating different functional response types to reflect natural conditions more closely. Our findings reveal that a shared predator both modifies the likelihood of consumer coexistence and introduces an emergent growthdefense trade-off. This expanded model highlights the greater dynamical richness of real-world scenarios and provides a baseline to explore the role of relative non-linearity in species coexistence within more complex systems.

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MS147

Global Dynamics in Systems Biology

Mathematical models in systems biology, often formulated as ODEs that may not be explicitly derived from first principles, can exhibit complex dynamical behavior. Understanding these dynamics, including features like equilibria, periodic orbits, connecting orbits and bifurcations across parameter ranges, provides insights into their long-term behavior. We employ a computational method based on combinatorial topology to analyze these dynamic structures. The approach constructs a combinatorial representation of state and parameter spaces and calculates associated algebraic topological invariants. Combined with analytical bounds, this combinatorial representation rigorously characterizes the dynamics within open regions of the parameter space. We demonstrate this approach on different models, including examples from population dynamics and gene regulatory networks.

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MS147

The Effect of Shared Habitat on Disease Recovery of Interacting Species and Their Community

Although the amphibian disease chytridiomycosis is responsible for devastating amphibian declines, collected data suggests that some species recover, albeit differences in recovery among species are responsible for community restructuring. By analyzing a mechanistic eco-evolutionary epidemic model, we identify and quantify mechanisms that facilitate or impede differences in disease recovery trajectories of species and their communities. We study the disease dynamics across scales by first investigating effects of foci mechanisms on individual species' recoveries and, then, their effects on the dynamics of the community as a whole. We specifically ask how *host defense strategies* of tolerance and resistance, *habitat overlap*, *overlap-dependent competition*, and *competitive trade-offs* impact species and community recoveries. Our species level analysis considers two interacting host species that evolve different defense strategies but interact either indirectly or directly through shared habitat. We find that the intensity of the negative effect of shared habitat depends on the host's defense strategy, with a more robust response of tolerance evolving hosts as compared to host species that evolve resistance. On the contrary, the community suffers from an asymmetry of hosts that is bias towards evolving tolerance and recovers faster for a community consisting of more resistance evolving species.

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MS148

Bifurcations of Piecewise Smooth Lotka-Volterra Systems with Intermittent Discontinuities

In this talk we will analyze the bifurcation scenario of 2D piecewise smooth Lotka-Volterra systems $Z = (X_1, X_2)$ where the smooth vector field X_1 is imposed when $y \leq \alpha_0$ with y downstairs. Also, X_1 is suspended when $y \geq \alpha_1$ with y upstairs. In the switching region we consider the Filippov's rules. This protocol can be applied, for example, in a disease treatment where the treatment is imposed when the quantity of health cells is small than a number α_0 and this intermittent treatment is suspended when the quantity of health cells is bigger than a number $\alpha_1 > \alpha_0$. We will search for bifurcations involving equilibria, limit cycles, kinds of basin of attraction and other minimal sets.

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MS148

Bifurcation of Isolated Invariant Tori in Piecewise Smooth Differential Systems Via Averaging Theory

In this work, we provide sufficient conditions for the existence and stability of invariant tori in three-dimensional piecewise linear differential systems. We consider systems that can be expressed in the form:

$$\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{k} \epsilon^i F_i(t, \boldsymbol{x}; \alpha) + \epsilon^{k+1} R(t, \boldsymbol{x}; \alpha, \epsilon), \qquad (2)$$

where F_i and R are piecewise functions defined by switching functions θ_i. Analyzing this system on $\mathbb{S}^1 \times D$, we define the time-T Poincar map:

$$\mathcal{P}_T : \Omega \to \Omega, \quad \boldsymbol{x} \mapsto \varphi_\epsilon(T, \boldsymbol{x}), \qquad (3)$$

where $\Omega = \{0\} \times D$, and φ_ϵ is the flow of the system. The existence of an invariant curve Γ such that $\mathcal{P}_T(\Gamma) = \Gamma$ implies an invariant torus in $\mathbb{S}^1 \times \mathbb{R}^2$. We show that this Poincar map can be seen as a smooth perturbation of the identity. Generalizing a method from [Cndido and Novaes, 2020], we apply our technique to any smooth system with a Poincar map near the identity. This approach allows the detection of isolated invariant tori in such systems, presenting a first analytical detection method for invariant tori in this class. We illustrate this with an example of a piecewise linear system with isolated tori.

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MS148

Resonant Grazing Bifurcations in Simple Impacting Systems

Many practical engineering systems include vibrations and impacts. Impacts are onset by grazing bifurcations, and these generate complex dynamics including chaos because the corresponding Poincare map has a highly nonlinear and destabilising square-root term. The main goal of this talk is to determine why leading-order approximations to such maps, such as the Nordmark map, are often only effective in extremely small parameter ranges. We find that this can be caused by a resonance effect, resulting in nearby period-doubling and saddle-node bifurcations. In order to numerically continue the curves of these bifurcations, we found it necessary to develop a new numerical tool that allows us to use root-finding methods such as Newton without the method failing by falling off the side of the square-root.

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MS148

Alpha-Delta Transitions in Cortical Rhythms as grazing bifurcations

The Jansen-Rit model of a cortical column in the cerebral cortex has been used to model large-scale brain activity as well as event-related potentials. It couples a pyramidal cell population with two interneuron populations, of which one is fast and excitatory and the other is slow and inhibitory. Using this model we investigate the mechanism of transition between alpha oscillations (associated with wakefulness in the frequency band from 8 to13 Hz) and delta oscillations (associated with sleep, below 4 Hz). For realistic parameter values, the non-linear coupling functions between populations have the form of discontinuous, threshold-like responses that approximate all-or-nothing switches. This structure allows us to interpret the system as a perturbation of a piecewise-smooth Filippov system with sharp transitions between distinct dynamical regimes. In the limit we can identify the boundary between alpha and delta oscillations as a discontinuity-induced grazing bifurcation of the periodic orbits corresponding to alpha oscillations. At the grazing the minimum of the pyramidal-cell output reaches the threshold for switching off the excitatory interneuron population, leading to a collapse in the excitatory feedback, giving a simple neurological mechanism for a phenomenon previously described as a "false bifurcation" (Forrester et al., 2020).

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MS149

Graph Based Operator Learning for PDEs and Molecular Dynamics

Operator learning has emerged as a powerful paradigm for solving partial differential equations (PDEs) by learning mappings between function spaces, enabling efficient and generalizable solutions to complex physical systems. Unlike traditional numerical solvers, graph-based transformers provide a structured and scalable way to capture spatial dependencies while remaining adaptable to arbitrary geometries. These models leverage attention mechanisms to effectively encode differential operators and boundary conditions, making them robust for a wide range of PDE-driven simulations, from fluid dynamics to elasticity. A natural extension of operator learning is in molecular dynamics (MD) simulations, where equivariance and uncertainty quantification play a crucial role. Molecular systems evolve under time-dependent, high-dimensional, and stochastic dynamics, necessitating models that respect underlying symmetries and provide reliable uncertainty estimates. By incorporating equivariant architectures, operator learning frameworks can ensure rotational, translational, and permutational invariance, making them well-suited for force-field learning and long-term trajectory predictions.

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MS149

On the Subtle Importance of Function Spaces in Koopman Eigenmode Decompositions

The majority of widely used Koopman eigenmode decompositions are done considering the Koopman operator acting on the Hilbert space $L^2(\mu)$ with respect to some measure μ. The focus of this talk concerns the interesting phenomenon that many discretization techniques are excited by eigenmodes of Koopman operators over functions spaces which are *strictly larger* than L^2. This raises a larger question - which computed eigenmodes are (1) "expected": approximations of L^2 Koopman eigenmodes, (2) "unexpected": approximations of eigenmodes in unintended function spaces, (3): "spurious": caused solely by the discretization?

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MS149

Physics-Informed Spectral Approximation of Koopman Operators

Koopman operators and transfer operators represent nonlinear dynamics in state space through its induced action on linear spaces of observables and measures, respectively. This framework enables the use of linear operator theory for supervised and unsupervised learning of nonlinear dynamical systems. Here, we propose a data-driven technique for spectral approximation of Koopman operators of continuous-time, measure-preserving ergodic systems that is asymptotically consistent and makes direct use of known equations of motion (physics). Our approach is based on a bounded transformation of the Koopman generator (an operator implementing directional derivatives of observables along the dynamical flow), followed by smoothing by a Markov semigroup of kernel integral operators. This results in a skew-adjoint, compact operator whose eigendecomposition is expressible as a variational generalized eigenvalue problem. We develop Galerkin methods to solve this eigenvalue problem and study their asymptotic consistency in the large-data limit. The computed eigenfunctions have representatives in a reproducing kernel Hilbert space, enabling out-of-sample evaluation of learned dynamical features. We will present numerical experiments performed with this method on integrable and chaotic low-dimensional systems demonstrate its efficacy in extracting dynamically coherent observables under complex dynamics.

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MS149

The Adaptive Koopman Operator Method for Solving Differential Equations

We propose the adaptive spectral Koopman (ASK) method to solve nonlinear autonomous dynamical systems. This novel numerical method leverages the spectral-collocation method and properties of the Koopman operator to obtain the solution of a dynamical system. Specifically, this solution is represented by Koopman operators eigenfunctions, eigenvalues, and Koopman modes. Unlike conventional time evolution algorithms such as Eulers scheme and the Runge-Kutta scheme, ASK is mesh-free, and hence is more flexible when evaluating the solution. Numerical experiments demonstrate high accuracy of ASK for solving both ordinary and partial differential equations. Further, ASK enables new designs of uncertainty quantification (UQ) methods, which can be much faster than state-of-the-art UQ methods. Finally, we will illustrate ASK's capability of solving optimization problems based on the gradient flow formula.

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MS150

Semiclassical Theory of the Koopman-Van Hove Equation

The phase space Koopman-van Hove (KvH) equation can be derived from the asymptotic semiclassical analysis of partial differential equations. Semiclassical theory yields the Hamilton-Jacobi equation for the complex phase factor and the transport equation for the amplitude. These two equations can be combined to form a nonlinear version of the KvH equation in configuration space. There is a natural injection into phase space, where it becomes the standard linear KvH equation, as well as a natural projection of phase space solutions back to configuration space. For integrable systems, the KvH spectrum is the Cartesian product of a classical and a semiclassical spectrum. If the classical spectrum is eliminated, then, with the correct choice of Jeffreys-Wentzel-Kramers-Brillouin (JWKB) matching conditions, the semiclassical spectrum satisfies the Einstein-Brillouin-Keller quantization conditions which include the correction due to the Maslov index. However, semiclassical analysis uses different choices for boundary conditions, continuity requirements, and the domain of definition. Finally, although KvH wavefunctions include the possibility of interference effects, interference is not observable when all observables are approximated as local operators on phase space; interference effects require nonlocal operations. I. Joseph, Semiclassical Theory and the Koopman-van Hove Equation, arXiv:2306.01865, J. Phys. A: Math. Theor. 56 (2023) 484001

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MS150

Koopman Theory on Infinite-Dimensional Spaces and Quantum Field Theory

Abstract: Quantum field theory offers a viewpoint on the space of fields defined over an infinite-dimensional background. We discuss how this perspective can be applied to the study of dynamical systems, especially in the context of Koopman theory. We formulate such fields on a bosonic Fock space and demonstrate how the dynamics lifts in this setting.

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MS150

Carleman Linearization-based Quantum Algorithms and Beyond

In this talk, we will explore recent advancements in quantum algorithms for solving nonlinear differential equations through Carleman linearization, with a focus on non-dissipative systems, particularly Hamiltonian systems and the structure-preserving aspect. We will then show several extensions of this approach to other scientific computing problems. We will provide error analysis, query/gate complexity, and numerical results to examine the quantum speedup compared with classical algorithms.

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MS150

Existence and Uniqueness of Solutions of the Koopman - Von Neumann Equation on Bounded Domains

The Koopmanvon Neumann equation describes the evolution of a complex-valued wavefunction corresponding to the probability distribution given by an associated classical Liouville equation. Typically, it is defined on the whole Euclidean space. The investigation of bounded domains, particularly in practical scenarios involving quantum-based simulations of dynamical systems, has received little attention so far. We consider the Koopmanvon Neumann equation associated with an ordinary differential equation on a bounded domain whose trajectories are contained in the set's closure. Our main results are the construction of a strongly continuous semigroup together with the existence and uniqueness of solutions of the associated initial value problem. To this end, a functional-analytic framework connected to Sobolev spaces is proposed and analyzed. Moreover, the connection of the Koopmanvon Neumann framework to transport equations is highlighted.

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MS151

Multiple Pulse-Like Perturbations Can Lead to Tipping of An Ecological System

We study the interplay of two critical transitions, B-tipping and a rate-dependent basin boundary crossing in an ecological system. One pulse of environmental change applied to the carrying capacity can lead either to tracking of the current stable state or to tipping to an alternate state depending on the strength and the duration of the pulse.

Moreover, we demonstrate, that applying a second pulse after the first one, that was still able to track the desired state, can lead to tipping though its rate is slow and it does not even cross the critical threshold. We explain this unexpected behavior in terms of the interacting timescales, the intrinsic ecological timescale, rate of environmental change but also the “movement’ of the basin boundaries separating the basins of attraction of the two alternative states.

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MS151

Slow Dynamics in Nonautonomous Hamiltonian Systems: Detecting Time-Dependent Non-Hyperbolic Regions

Typical Hamiltonian systems are known to exhibit non-hyperbolic behavior manifesting itself in slow dynamics. Because this implies long lifetimes around certain phase space regions, around last KAM surfaces in particular, the term stickiness is also used for this phenomenon. In this talk we demonstrate that a similar behavior can be observed in systems subjected to parameter drift. In such cases, tori and chaotic seas have time-dependent shapes and sizes, they are so-called snapshot tori and chaotic seas, respectively. First, we show that these chaotic seas are not necessarily fully chaotic. Chaos can be regarded as the area where the stable and unstable foliations of the problem (which are now also time-dependent) possess intersection points. However the snapshot chaotic sea can be larger than this area, thereby containing what we call time-dependent non-chaotic regions. Then, within these regions we can further distinguish the dynamics by applying the Ensemble-Averaged Pairwise Distnace (EAPD) method and detecting regions where slow dynamics persists for a finite time. These so-called time-dependent non-hyperbolic regions can be found on the border of the last still intact snapshot tori, and can be regarded as the time-dependent analogs of sticky dynamics. We will also show an example of this behavior in a chaotic map modelling magnetic field lines in a limiter-perturbed tokamak plasma.

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MS151

Orbital Dynamics in Galactic Potentials under Mass Transfer

Time-dependent potentials are common in galactic systems that undergo significant evolution, interactions, or encounters with other galaxies, or when there are dynamic processes like star formation and merging events. Recent studies show that an ensemble approach along with the so-called snapshot framework in dynamical systems theory provide a powerful tool to analyze the time-dependent dynamics. In this work, we aim to explore and quantify the phase space structure and dynamical complexity in time-dependent galactic potentials consisting of multiple components. We apply the classical method of Poincar surface of section to analyze the phase space structure in a chaotic Hamiltonian system subjected to parameter drift. This, however, makes sense only when the evolution of a large ensemble of initial conditions is followed. Numerical simulations explore the phase space structure of such ensembles while the system undergoes a continuous parameter change. The pair-wise average distance of ensemble members allows us to define a generalized Lyapunov-exponent, that might also be time dependent, to describe the system stability. We provide a comprehensive dynamical analysis of the system under circumstances where linear mass transfer undergoes between the disk and bulge components of the model.

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MS152

Single-Mode Equations of Convection with Large-Scale Damping

This work presents single-mode equations-based reduced-order modeling of connection with large-scale damping, which features well-organized columnar structures. We discuss two examples of large-scale damping: stably stratified temperature gradient in salt-finger convection and Darcy law damping for convection in a porous medium. We obtain single-mode equations obtained from a severely truncated Fourier expansion in the horizontal. For salt-finger convection, strongly nonlinear staircase-like solutions having, respectively, one (S1), two (S2) and three (S3) regions of mixed salinity in the vertical direction are computed using numerical continuation, and their stability properties are determined. Secondary bifurcations of S1 lead either to tilted-finger (TF1) or to travelling wave (TW1) solutions, both accompanied by the spontaneous generation of large-scale shear. For convection in a porous medium, the single-mode solutions resembling steady convection rolls reproduce the qualitative behavior of root-mean-square and mean temperature profiles of time-dependent states at high Rayleigh numbers from direct numerical simulations (DNS). We also show that the single-mode solutions are consistent with the heat-exchanger model that describes well the mean temperature gradient in the interior. The single-mode solutions close to the high wavenumber onset

are in excellent agreement with 2-D DNS in small horizontal domains and compare well with 3-D DNS.

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MS152

Computing Invariant Solutions and Their Ghosts in Navier-Stokes Without Suffering from Chaos

Invariant solutions of the governing equations, such as unstable equilibria and periodic orbits, are believed to serve as elementary building blocks of chaotic fluid flows and to play a major role in the emergence of patterns and coherent flow structures. Close to a saddle-node bifurcation, when two invariant solutions collide and annihilate, the flow behavior can closely resemble that of the solution at the bifurcation point, even though the solution itself does not exist at the studied parameter value. Therefore, patterns and coherent flow structures may emerge as a result of the dynamics feeling a non-existing invariant solution, a phenomenon called the ghost of a solution. We use recently developed variational methods to formalize the concept of ghosts, follow ghost states in parameter space and demonstrate how even non-existing invariant solutions may control the behaviour of the chaotic flows, including 3D Rayleigh-Benard convection. This work was suppored by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant no. 865677).

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MS152

Hopf Bifurcation in Two-Dimensional Salt-Fingering Convection

This work studies jet formation in two-dimensional salt-finger convection in an asymptotically derived modified RayleighBénard convection (MRBC) model, valid in the geophysical and astrophysically relevant limit in which the solute diffuses much more slowly than heat. In these equations, convection is driven by a destabilizing salinity gradient while the effects of the stabilizing temperature gradient manifest themselves as an additional anisotropic dissipation acting on large scales. The MRBC system is specified by two external parameters: the Schmidt number Sc (ratio of viscosity to solutal diffusivity) and the Rayleigh ratio Ra (ratio between the Rayleigh numbers of the destabilizing solutal stratification and the stabilizing thermal stratification). Two distinct Ra regimes are explored for fixed Sc = 1. The system develops a horizontal jet structure that is maintained self-consistently by turbulent fluctuations. For intermediate Rayleigh ratios, the MRBC model captures the relaxation oscillations superposed on the jet structure. For smaller Rayleigh ratios, the MRBC model reveals the existence of statistically steady jets. A three-component phenomenological model consisting of a linearly growing mode, a linearly damped mode and a mean mode is proposed to explain the observed transition from statistically steady jet structure to jets with superposed oscillations that takes place with increasing Rayleigh ratio through a Hopf bifurcation.

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MS153

Wilton's Ripples in Sheets of Bimodal Waves

The bifurcation structure of small amplitude periodic traveling capillary-gravity waves is discussed. At special parameter values, a type of resonance, the linear problem has two dimensional kernel. The nonlinear problem in this configuration has solutions which are near a superposition of the two harmonics in the kernel of the linear problem. Wilton famously described this bifurcation stating that branches of nonlinear solutions bifurcate from linear waves for only particular ratios of the two harmonics. Recently, sheets of traveling ripples have been proven to exist near the resonant configuration with almost every ratio of the two harmonics. Both the classic branches and the sheets of waves are asymptotically approximated and numerically computed. The classic branches of Wilton ripples are observed to be embedded within the sheets.

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MS153

Traveling Front Solutions in Diffusive SIS Model

We show the existence of traveling front solutions in diffusive SIS epidemic model in various parameter regimes. In the regime when the infected population diffuses slower than the susceptible population, we show the existence of traveling wave solutions for each fixed positive speed and describe their structure and dependence on the wave speed which is varied from 0 to infinity. In the regime when the infected population diffuses faster than the susceptible population, we show that the spread of the disease can be described by Burgers-FKPP equation and derive a bound for the speeds of the fronts in this regime.

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MS153

Asymptotic Attraction with Algebraic Rates Toward Fronts of Dispersive-Diffusive Burgers Equations

Burgers equation is a classic model, which arises in numerous applications. At its very core it is a simple conservation law, which serves as a toy model for various dynamics phenomena. In particular, it supports explicit heteroclinic solutions, both fronts and backs. There has been substantial interest in considering dispersive and/or diffusive modifications, which present novel dynamical paradigms in such simple setting. More specificaly, the KdV-Burgers model has been showed to support unique fronts (not all of them monotone!) with fixed values at $\pm\infty$. Many authors have studied the question of stability of monotone (or close to monotone) fronts. Recently, Barker, Bronski, Hur and Yang have extended these results in several different directions. They have considered a wider range of models. The fronts do not need to be monotone, but are subject of a spectral condition instead. Most importantly the method allows for large perturbations, as long as the heteroclinic conditions at $\pm\infty$ are met. That is, there is asymptotic attraction to the said fronts or equivalently the limit set consist of one point. The purpose of this paper is to extend these results of by providing explicit algebraic rates of convergence as $t \to \infty$. We bootstrap these results for two important examples namely: KdV-Burgers and the fractional Burgers problem. These rates are likely not optimal, but we conjecture that they are algebraic nonetheless.

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MS153

On the Pattern Formation on a Model for Urban Crime: Exploring Hotspot Formation and Suppression

We investigate pattern formation in the model of the spatiotemporal dynamics of urban crime with law enforcement. The model is a system of nonlinear partial differential equations representing attractiveness value, crime density, and police density. We employ bifurcation and perturbation theories to understand the pattern formation mechanism in this model. We present the results on bifurcating branches and the derivation of amplitude equations. We further use amplitude equations to explore hotspot emergence and suppression. Our analysis is a natural extension from previous works on the same system but with no law enforcement: [SIAM J. Math. Anal., Vol. 44, No. 3, pp. 1340-1358] and [SIAM J. Applied Dynamical Systems, Vol. 9, No. 2, pp. 462-483]. We supplement the presentation with relevant numerical simulations to show how the changes in the system parameters affect the behavior of the solutions.

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MS154

Control Coherent Koopman Modeling with Applications to Robotics

There is a fundamental limitation to the current Koopman Operator theory when applying it to dynamical systems with control. Prior works assume that control inputs are linearly involved in state equations and apply least squares estimate for approximating the input matrix. Bilinear approximation provides better accuracy, but the resultant Koopman model is no longer linear in control. In this talk, a new approach based on physical system modeling is presented to extend the Koopman method to a broad class of non-autonomous systems with control. Control Coherent Koopman modeling allows us to represent nonlinear controlled systems as linear time-invariant systems without control approximation. Dynamics of actuators are modeled as subsystems possessing independent state variables, which are driven by a source control input linearly. It is shown that the Koopman modeling problem is reduced to that of standard autonomous systems and that this actuator subsystem modeling applies to broad engineered dynamical systems. Next, the Control Coherent Koopman modeling is applied to diverse robot control problems, including multi-cable manipulation, rimless wheel dynamic walking, and pushing manipulation, all of them are switched dynamical systems. Although governing equations must be switched as the robot makes and breaks contact with an object or a ground, a unified, global Koopman model allows us to apply linear Model Predictive Control to these otherwise complex nonlinear systems.

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MS154

Koopman Lqr Control of Nonspherical Shape Modes of a Microbubble for Biomedical Applications

In this work, we apply Koopman LQR to control nonspherical shape oscillations of gas bubbles in water. Specifically, we use the Reddy & Szeri model for bubble shape modes, and a combination of the Hankel-DMD and SINDy algorithms to approximate its Koopman eigenfunctions. The LQR controller is then formulated in terms of these eigenfunctions using a standard cost functional, and the optimal control problem is solved via the classical Algebraic Riccati Equation. However, in prior work, the eigenfunctions used in the KLQR controller were functions of the underlying dynamical state. This both limited which kinds of targets could be set and required full-state access. Here we perform a slight reformulation: we allow the eigenfunctions to become functions of generic observables. Ultimately, this amounts to a simple change of variables; but, in turn, it also allows for a broad generalization of control to arbitrary observables while still retaining the useful closure properties of the Koopman operator acting on sets of eigenfunctions. Additionally, it obviates the need for full-state access. We then apply this formulation of KLQR to control several observables related to the bubble's shape, thereby driving its dynamics. After demonstrating its success, we analyze the resulting control signals.

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MS154

Koopman-Driven Grip Force Prediction Through EMG Sensing

Conditions like stroke or multiple sclerosis impair hand function, greatly limiting an affected persons daily activities. While traditional rehabilitation methods that involve physiotherapists often lack the necessary intensity, robotic rehabilitation significantly enhances outcomes in restoring hand function. Innovative methods using surface electromyography (sEMG) further adapt the device's force output to the user's needs, enhancing rehabilitation results. Leveraging flexible signal-processing steps and a novel data-driven approach based on Koopman operator theory, coupled with problem-specific data lifting techniques, this study aims to achieve accurate force estimations and predictions during medium wrap grasps using single-position sEMG measurements. We conducted sEMG measurements on 13 subjects at two forearm positions, validating the results with a calibrated hand dynamometer. Optimal signal processing parameters were identified through multi-step sensitivity analysis. The Koopman-based methodology for estimating and short-term predicting grip force from processed sEMG signals proved robust concerning precise electrode positioning, as the effect of sensing position on error metrics was non-significant. The algorithm executes exceptionally fast, processing, estimating, and predicting a 0.5-second sEMG signal batch in 30 ms time frame, facilitating real-time implementation.

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MS154

Koopman Modeling for Kinetostatic Protein Folding

Protein folding, fundamental to biological processes, involves complex conformational changes that are challenging to model. Kinetostatic compliance method (KCM), which is a recent effective modeling approach, is based on modeling protein molecules as serial nano-linkage mechanisms with hyper degrees of freedom. While these intricate dynamics present significant modeling challenges, the folding process often follows dominant pathways that can be captured by low-dimensional representations. Despite extensive research to uncover these dominant dynamics, existing methodologies often fail to produce models that accurately capture them, hindering precise prediction and manipulation in critical biomedical and nano-robotics applications. This work addresses this gap by utilizing the Koopman operator framework to discover and exploit the dominant dynamics throughout the folding process, substantially outperforming existing methods. Numerical simulations utilizing the KCM approach on protein backbones confirm the effectiveness of the proposed framework.

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MS155

Path Integrals and Stochastic Transitions

Traditionally, stochastic processes are modelled using either a Fokker-Planck PDE approach, or a Langevin SDE approach. There is also a third way: the functional or path integral. Originally developed by Wiener in the 1920s to model Brownian motion, path integrals were famously applied to quantum mechanics by Feynman in the 1950s. However, they also offer much to classical stochastic processes. In this talk I will introduce the formalism, focussing on the dominant contribution to the path integral when the noise is weak. There exists a remarkable correspondence between the most-probable stochastic paths and Hamiltonian mechanics in an effective potential [1,2,3]. I will then discuss applications, including reaction pathways conditioned on finite time [2]. We demonstrate that the most probable pathway may be very different from the usual minimum energy path used to calculate the average reaction rate. [1] Ge, Hao, and Hong Qian. Int. J. Mod. Phys. B 26.24 1230012 (2012) [2] Fitzgerald, Steve, et al. J. Chem. Phys. 158.12 (2023) [3] Honour, Tom and Fitzgerald, Steve. J. Phys. A 57 175002 (2024)

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MS155

Transients and Tipping in Ecological Systems

Transients and tipping are two kinds of dynamics that are observed in ecological systems and have received increasing attention. I will explain why the study of many aspects of tipping can be subsumed under studies of transient dynamics. Many key questions remain in the study of transient dynamics including identifying whether a system is in a transient state and how one can predict when a transient state will end. The latter is a feature that might look like tipping, so it is perhaps not surprising that ideas developing in the context of understanding tipping can be used to understand when some transients will end. I will present results of this form and also describe open questions. Applications to understanding and management of ecological systems will also be presented.

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MS155

Nonautonomous Differential Equations in the Presence of Bounded Noise

Nonautonomous systems in the presence of noise are widespread in applications. We focus on the case of bounded noise. This is often a more realistic modelling assumption, since physical quantities only vary within certain bounds. Thus, qualitative dynamical changes become identifiable in terms of interactions between localized objects, which is often not possible in the case of unbounded noise. Moreover, the dynamics of a random dynamical system with bounded noise can be effectively described at a topological level as a deterministic set-valued dynamical system, which captures the compounded behavior of the underlying random system by evolving initial conditions under all possible realizations of the noise, while omitting detailed probability information. However, set-valued dynamical systems present significant analytical challenges, as they operate on the collection of all compact subsets, which does not form a Banach space. This limitation poses a well-known obstacle for both theoretical and numerical methods. As a result, conducting bifurcation analysis of attractors in set-valued dynamical systems is a notoriously difficult task. We provide a nonautonomous generalization of the so-called boundary map to describe the behaviour of nonautonomous invariant sets for set-valued dynamical systems by keeping track of the evolution of the boundary.

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MS156

Reconstructing Networks and Hypernetworks of Coupled Oscillators from Time Series

We are interested in weakly coupled Kuramoto oscillators and aim to determine their network structure from time series data. The main challenge here is that the problem is not well-posed: two different network models can produce identical time series if theres noise. As a result, it is impossible to reconstruct the exact model or network structure. To overcome this issue, rather than reconstructing the complete model, we focus on identifying the simplest form of the model that can replicate the observed dynamics. This involves using the normal form, which captures the core features of the dynamics. Our method uses least-squares fitting to achieve this. Fitting the normal form, we also don't need many data points, making the method efficient and robust. By examining the data and fitted terms, we further establish an explicit bound on the error in the reconstructed coupling coefficients. We illustrate our results with numerical simulations.

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MS156

Hypernetworks with Electrochemical Oscillators

Electrochemical oscillators can be coupled in diverse configurations with various frequency distributions. By experimentally measuring their phase dynamics, phase models can be constructed to predict synchronization patterns that arise from specific coupling topologies and resonant frequency combinations. Here, we demonstrate that coupling based on pairwise interactions can be designed to induce hypernetworks, which depend on interactions among triplet phase differences. A key finding is the presentation of distinct regular networks that display nearly identical hypernetwork configurations. We interpret the experimental results using coupled Kuramoto oscillators, describing the mechanism for emergent hypernetworks through phase coordinate transformations. These findings open new possibilities for hypernetwork-based descriptions of complex systems, enabling the effective engineering of interactions through pairwise networks and triplet resonances.

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MS156

Self-Consistent Approach to Synchronization on Hypergraphs

Synchronization of phase oscillators on hypergraphs has been studied for the all-to-all case or for random hypergraphs using mean-field approximations. While these approaches are useful, they do not capture the full hypergraph structure and might not be appropriate to describe individual hypergraphs. To overcome these limitations, we study synchronization on hypergraphs using Kuramoto's original, self-consistent method. We obtain a set of nonlinearly coupled equations for the local order parameters that depend on the full hypergraph adjacency tensors. By doing a weakly nonlinear analysis of these equations, we find conditions for an explosive synchronization transition. Generalizing previous results, we find that the critical coupling strength for the onset of bistability depends on eigenvectors of the pairwise adjacency matrix and the higher-order adjacency tensor. We illustrate our results with numerical simulations.

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MS156

Phase Reduction for Delay-Coupled Oscillators

In many real-life networks systems, it takes a significant time for signals to travel from node to node, leading to time delays in the coupling. Experiments show that coupling delays have a crucial and often counterintuitive effect on collective phenomena, including the synchronization of coupled oscillators. In this talk, I will introduce a phase reduction technique for delay-coupled oscillators, which gives a systematic way to derive equations for the phases of coupled oscillators. The resulting phase model is lower dimensional than the original model (in fact, it is finite dimensional while the original model is infinite dimensional), which facilitates further analysis of synchronization phenomena. I will first discuss the mathematical approach to phase reduction in delay-coupled oscillators, including the approach to compute higher-order terms (i.e. terms of order at least 2) in the coupling parameter. By means of an illustrative example, I will then show how including these higher-order terms yields more accurate predictions of synchronization behavior.

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MS157

Network Physiology: Dynamic Networks of Organ Interactions Building the Human Physiolome

The human organism is an integrated network where physiological systems continuously interact to synchronize functions. Physiologic interactions occur at multiple spatiotemporal scales to generate various states at the organism level. Disrupting network communications can cause dysfunction of individual systems or collapse of the organism. We initiated a multidisciplinary field, Network Physiology, to understand how systems and organs integrate as a network to maintain health. Utilizing concepts and approaches from nonlinear dynamics, statistical and computational physics we present a new framework to identify and quantify dynamic networks of diverse organ systems. We focus on inferring interactions from continuous synchronized recordings of key physiologic variables to establish dynamic laws of organ cross-communications, and we track the evolution of physiological networks in response to transitions across states. We uncover: (i) new aspects of neural plasticity in brain-brain networks of brain waves across cortical locations and their relation to basic states; (ii) brain-organ networks as a signature of dynamic control and basic states; (iii) principles of integration underlying organ-organ networks. We demonstrate how physiologic network connectivity relates to global behaviors, states and functions. The presented findings are initial steps towards building a first atlas of dynamic network interactions among physiological systems and subsystems, the Human Physiolome.

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MS157

Best Time to Take Your Blood Pressure Meds?

Sex influences cardiovascular disease, and the timing of onset of acute cardiovascular events exhibits circadian rhythms. Kidney function also exhibits sex differences and circadian rhythms. How do the natriuretic and diuretic effects of diuretics, a common treatment for hypertension that targets the kidneys, differ between the sexes? And how do these effects vary during the day? To answer these questions, we conducted computer simulations to assess the effects of loop, thiazide, and K+-sparing diuretics.

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MS157

Gut Instincts: A Data Driven Approach to Mouse Colon Modeling

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 colonic motor complexes (CMC) 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. We aim to create a model that reproduces the global dynamics observed in optogenetic and calcium measurements of mouse colons. In particular, we focus on how certain coupling parameters affect the speed and frequency of the observed CMC and ICC waves and how other parameters affect the robustness of the model.

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MS158

Recurrence Networks Reveal Shared Causal Drivers of Time Series

Many experimental time series measurements share unobserved causal drivers. Examples include genes targeted by transcription factors, ocean flows influenced by large-scale atmospheric currents, and motor circuits steered by descending neurons. Reliably inferring this unseen driving force is necessary to understand the intermittent nature of top-down control schemes in diverse biological and engineered systems. Here, we introduce a new unsupervised learning algorithm that uses recurrences in time series measurements to gradually reconstruct an unobserved driving signal. Drawing on the theory of skew-product dynamical systems, we find that recurrences shared across response time series implicitly define a glass-like recurrence graph. As the quality of experimental data improves, this graph undergoes a percolation transition manifesting as weak ergodicity breaking for random walks on the induced landscape—revealing the shared driver's dynamics, even in the presence of strongly corrupted or noisy measurements. Through extensive benchmarks against classical and neural-network-based signal processing techniques, we demonstrate our method's strong ability to extract causal driving signals from diverse real-world datasets spanning ecology, genomics, fluid dynamics, and physiology.

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MS158

Quantum Optimization Methods Via Hamiltonian

Dynamics

Quantum computation technology has drawn significant attention in recent years, particularly due to its promise to accelerate the solution of sophisticated computational tasks, such as optimization and machine learning. Among the extensive literature in the field, an emerging paradigm involves designing novel quantum optimization algorithms via dynamical systems. In this talk, we introduce Quantum Hamiltonian Descent (QHD), a quantum optimization algorithm inspired by the interplay between accelerated gradient descent and Hamiltonian mechanics. Similar to its classical counterpart, a global convergence result for convex optimization is obtained through Lyapunov analysis. Notably, for nonconvex problems, QHD exhibits drastically different behavior due to quantum interference. The quantum advantage of QHD is investigated through both theoretical and numerical means. We will also discuss the natural generalization of QHD using higher-order information, which leads to a new class of quantum algorithms with faster convergence and potentially better global performance.

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MS158

Deep Learning and Oscillatory Dynamical Systems

In this presentation, we explore several crucial challenges associated with developing robust deep learning models for computing the flow of oscillatory dynamical systems. Key topics of discussion include the selection of an optimal training data distribution, strategies for effective sampling from this distribution, the creation of balanced loss functions and regularization, and the identification of suitable network architectures. We will demonstrate our methodologies and discuss the practical implications and potential solutions for these challenges.

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MS158

Alternating Mirror Descent for Constrained Min-Max Games

We study two-player bilinear zero-sum games with constrained strategy spaces. An instance of natural occurrences of such constraints is when mixed strategies are used, which correspond to a probability simplex constraint. We propose and analyze the alternating mirror descent algorithm, in which each player takes turns to take action following the mirror descent algorithm for constrained optimization. We interpret alternating mirror descent as an alternating discretization of a skew-gradient flow in the dual space, and use tools from convex optimization and modified energy function to establish an $O(K^{-2/3})$ bound on its average regret after K iterations. This quantitatively verifies the algorithm's better behavior than the simultaneous version of mirror descent algorithm, which is known to diverge and yields an $O(K^{-1/2})$ average regret bound. In the special case of an unconstrained setting, our results recover the behavior of alternating gradient descent algorithm for zero-sum games which was studied in (Bailey et al., COLT 2020).

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MS159

Hegemony of the Few in Neural Population Bursts

GABAergic synaptic connections are excitatory early in development, just like glutamatergic connections. There is also little or no spatial structure in neural connectivity. In spite of the purely excitatory connectivity, the neural networks often exhibit population bursts of electrical activity. Later in development, the GABAergic connections transition to inhibitory, as they typically are in the mature brain. We use neural network simulations to show that as the GABA synapse polarity transitions from excitatory to inhibitory some unexpected changes occur in the population bursts of neural activity; the time between bursts initially increases, as expected, but later it decreases. This decrease is paradoxical: how can making a subset of neurons more inhibitory produce an increase in the frequency of bursting and thus an overall increase in network activity? This phenomenon reflects the activity of a small set of neurons, which we call "intermediate neurons", that are neither silent between population bursts nor tonically active between bursts. We demonstrate how these intermediate neurons control the onset of each population burst, and use bifurcation analysis to identify what makes them special.

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MS159

Intrinsic Neuronal Properties Shape Local Circuit Inhibition in Primate Prefrontal Cortex

In vitro recordings of macaque cortical neurons reveal spike frequency adaptation (SFA) in response to constant stimuli, even when neurons are isolated from their networks. This adaptation also appears in vivo during behavioral tasks. However, the role of intrinsic SFA in response patterns during in vivo experiments is unclear. To investigate this, we analyzed recordings from the lateral prefrontal cortex (LPFC) of macaques in two settings: a) in vivo, during a visually guided saccade (VGS) task, and b) in vitro brain slices. Neurons were categorized as broad spiking (BS) and narrow spiking (NS). SFA was quantified by fitting spike density functions with an exponential decay model. Both BS and NS neurons displayed SFA in vivo and in vitro, though NS neurons reached a higher asymptote in vitro. We developed a data-driven hybrid model where SFA in NS cells was driven by inputs from BS excitatory cells. The model's NS cells had wider temporal response profiles than observed in VGS task data, which was corrected by adding a feedforward inhibitory component targeting NS cells. This talk will provide an overview of these findings.

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MS159

Photoperiodic Encoding in a Network of Circadian Oscillators

The suprachiasmatic nucleus (SCN) located above the optic chiasm is thought of as the brain's central pacemaker, modulating circadian ($\tilde{2}$4hr) rhythms in basic physiological processes such as activity, metabolism, and hormone levels. Heterogeneous populations of cells in the SCN function as circadian oscillators that can synchronize with each other and/or entrain to light signals from the retina. Amazingly, SCN neurons can predict the onset and offset of light each day by adapting their coupling. We developed a mathematical model of this system, which we use to make predictions about day-to-day activity patterns. We compare our model predictions with wrist-wearable activity and sleep data from thousands of medical interns with changing shift schedules. The model has many interesting dynamical features, including synchronization, phase locking, and desynchrony between oscillators, which have important implications for circadian and seasonal timing.

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MS159

Saddle-Node Separatrix-Loops and Neuronal Network Dynamics

In this talk, I will present the unfolding of a codimension-three saddlenode to saddle separatrix-loop bifurcation found in neural mass models with characteristic nullcline geometry. This bifurcation involves a heteroclinic loop between a non-hyperbolic and a hyperbolic saddle, representing a fundamental, generic structure in such systems. We focus on the minimal, planar case where the non-hyperbolic point undergoes a saddle-node bifurcation. Employing Poincaré return maps, we identify a minimal set of perturbations that generates all possible qualitative behaviours near this non-central SNICeroclinic loop. Our results show that adjusting three key unfolding parameters enables transitions between a heteroclinic loop and other dynamic behaviours, including a persistent homoclinic loop, saddle-node on an invariant circle (SNIC), and stable periodic orbits or equilibria. This reveals a novel bifurcation structure we term a SNICeroclinic bifurcation, which we propose serves as an organising centre for complex neural transitions involving saddle-node-saddle separatrix loops.

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MS160

Fast Bayesian Identification of Nonlinear Dynamics (BINDy) in Scarce and Noisy Data

The Sparse Identification of Nonlinear Dynamics (SINDy) framework has been shown to be effective in learning interpretable and parsimonious models directly from data. However, existing SINDy derivatives can be computationally expensive and may struggle to learn the correct model equations from noisy and small datasets. We propose a Bayesian extension to SINDy for learning equations from data. Our method shows more robust capability in learning the correct model in the low-data limit, as it sparsifies the model based on both the value and the distribution of the parameters during regression, and uses the marginal likelihood (evidence) to rank and select the candidate models. The proposed method uses Laplace's method to approximate the Bayesian likelihood and evidence, avoiding the need for computationally expensive sampling. This results in a significant speedup in computation compared to other Bayesian SINDy methods, while still achieving comparable or better performance than existing methods such as Ensemble-SINDy. We demonstrate the effectiveness of the proposed method on a variety of problems, including learning the Lotka-Volterra equations from real-life observation of Lynx-Hare population dynamics, and the Lorenz system using tens of noisy data points. Moreover, our approximation of the Bayesian likelihood and evidence also can be used to compute potential information gain, which can inform optimal sampling and effectively form an active learning problem.

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MS160

Statistical Mechanics of Dynamical System Identification

Recovering dynamical equations from observed noisy data is the central challenge of system identification. We develop a statistical mechanical approach to analyze sparse equation discovery algorithms, which typically balance data fit and parsimony via hyperparameter tuning. In this framework, statistical mechanics offers tools to analyze the interplay between complexity and fitness, in analogy to that done between entropy and energy. To establish this analogy, we define the hyperparameter optimization procedure as a two-level Bayesian inference problem that separates variable selection from coefficient values and enables the computation of the posterior parameter distribution in closed form. A key advantage of employing statistical mechanical concepts, such as free energy and the partition function, is in the quantification of uncertainty, especially in the low-data limit that is frequently encountered in real-world applications. As the data volume increases, our approach mirrors the thermodynamic limit, leading to distinct sparsity- and noise-induced phase transitions that delineate correct from incorrect identification. This perspective of sparse equation discovery is versatile and can be adapted to various other equation discovery algorithms.

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MS160

LyapInf: Data-Driven Lyapunov Function Inference for Stability Analysis of Nonlinear Dy Namical Systems

Analyzing the stability of a nonlinear dynamical system is central to understanding system behavior and designing controllers, and we use a Lyapunov function for this purpose. It is possible to guarantee the stability of a system if one can find a Lyapunov function that is positive definite and decreasing over time along the orbit of the system, thus providing a sufficient condition for stability. A Lyapunov function also characterizes an estimate of the domain of attraction, which indicates the region under which the system states asymptotically converge to equilibrium. The construction of a Lyapunov function is done analytically and ad hoc for certain nonlinear systems. However, doing so for systems with high nonlinearities and different dimensions is a challenging task. To address this problem, we present a data-driven method for discovering Lyapunov functions, called Lyapunov function Inference (LyapInf). This new method fits a quadratic Lyapunov function to the state trajectory data of the dynamics via optimization, where the process of inferring a Lyapunov function is based on the non-intrusive model reduction method of Operator Inference. This method learns one of many possible Lyapunov functions that ensures stability and estimates the domain of attraction with or without access to the system model. In this work, we demonstrate this new method on several numerical examples.

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MS160

Dynamical stability Guarantees for Data-Driven Quadratically Nonlinear Models

Quadratically nonlinear reduced-order models (ROMs) are commonly used for approximating the dynamics of fluids, plasmas, and many other physical systems. However, it is challenging to a-priori guarantee the local or global dynamical stability of reduced-order models built from data. For instance, a minimal requirement for physically-motivated ROMs is long-time boundedness for any initial condition, yet many ROMs in the literature still fail this basic requirement. For quadratically nonlinear systems with energy-preserving nonlinearities, the Schlegel and Noack trapping theorem [Schlegel and Noack 2015] provides conditions for long-time boundedness to hold. This analytic theorem was subsequently incorporated into system identification and machine learning techniques in order to produce a-priori bounded models directly from data [Kaptanoglu 2021, Ouala 2023, Goyal 2023]. However, many dynamical systems exhibit weak breaking of the quadratically energy-preserving nonlinear structure required for the trapping theorem. To address this important case, we present recent work that relaxes the quadratically energy-preserving constraint and derives local stability guarantees for data-driven models. The analytic results are subsequently used with system identification techniques to build models with a-priori local stability properties [Peng 2024]. Lastly, we comment on alternative methods and future work for promoting dynamical stability in data-driven models.

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MS161

A Flexible Theory for the Dynamics of Social Populations: Within-group Density Dependence and Between-group Processes

The implications of population structures are well-studied in many ecological contexts. Surprisingly, relatively little theory has been developed regarding the implications of social structure for population dynamics. The dynamics of socially structured populations are unique because social groups themselves may split, fuse, and compete. Here, we clarify the important role such between-group processes play in the dynamics of social populations. We analyze a model that includes births, deaths, migration, fissions, fusions, and between-group competition and allows for either positive or negative density dependence in each. The effect of between-group processes is mediated by how they influence the stable group-size distribution and interact with within-group density dependence. We clarify that density dependence in social groups does not lead to density dependence at the population level. However, between-group processes can lead to either negative or positive density dependence at the population level, even if birth and death rates do not directly depend on population size. We extend the model to consider various classes of individuals such as age and sex, and also clarify how it can be used to study the evolution of between-group processes. Overall, our results show that population dynamics in social animals depend on within-group density dependence, between-group processes, and interactions between them and provide a flexible modeling framework for social populations.

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MS161

How Groups Reproduce is Critical in Multilevel Selection

Models of multilevel selection are typically difficult to analyze exactly unless groups reproduce by "cloning" themselves. However, it is often more realistic to assume groups reproduce by breaking into pieces (fissioning). We describe a parameterized model of group reproduction, with cloning at one extreme and random fission at the other. We then demonstrate profound changes as the parameter is varied, including group-level branching, and faster and more complete evolution of cooperation.

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MS162

Regulating Blood Glucose Levels Based on Feasible Interventions: Between Mathematical Modeling and Data-Driven Approaches

In the data-driven era, deep learning and reinforcement learning approaches have been widely applied to investigate biomedical signals and measured variables, such as blood glucose levels. However, traditional models based on ordinary differential equations for simulating glucose dynamics have proven effective in meeting data requirements and providing a foundation for physiological understanding. To design optimal interventions for managing glucose patterns in patients with diabetes mellitusfrom multiple daily insulin injections to closed-loop systems through continuous glucose monitoring and automated insulin deliveryvarious strategies have been proposed, including basal and bolus insulin calculations, proportional-integral-derivative (PID) control, model predictive control, and reinforcement learning. Some of these approaches are knowledge-based, while others are data-centric. Is it possible to integrate these two contrasting approaches to regulate glucose levels in diabetic patients effectively in clinical settings?

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MS162

Data-driven Mathematical Modelling of the HPA Axis in Humans and its Integration with Sleep

The hypothalamic-pituitary-adrenal (HPA) axis is the endocrine system controlling dynamic responses to stressors. Mathematical modelling and experiments in rodents have shown that negative feedback loops underpin rhythmic activity within this axis, but a human equivalent model is lacking. This talk outlines a data-driven approach to calibrate a model of hormonal rhythms in the human HPA axis. The model is written in terms of Delay Differential Equations (DDEs) and predicts the conditions that lead to pulsatile secretion of cortisol and ACTH hormones with ultradian (¡24 hrs) periodicity. Oscillatory solutions arise via a Hopf bifurcation, physiologically determined by a balance between the hypothalamic circadian drive and feedback loop delay. The model was calibrated using data consisting of cortisol and ACTH plasma hormone profiles measured every 20 minutes over 24 hrs in 10 healthy individuals. Wavelet analysis revealed unique patterns in hormonal rhythms across individuals, including variability quantification. Model fitting yielded specific parameter values for each participant and estimated cohort distributions. Bifurcation analysis determined the conditions needed to sustain ultradian rhythmicity, and the sensitivity of the oscillatory solution to parameter variability. Coupling a model of sleep regulation will help explore the interactions between stressors and sleep disruptions, offering insights into how circadian rhythms affect neuroendocrine regulation in humans.

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MS162

Linking Biological Rhythms, Intercellular Signaling, and Metabolic Disease

My laboratory investigates how dysregulated circadian rhythms control obesity and metabolic disease. Glucocorticoid circadian rhythms are main drivers of the daily wake-rest cycle in humans, and chronic stress and insufficient sleep has been shown to disrupt these crucial daily glucocorticoid hormone oscillations. I will describe how we use live-cell imaging, single cell analysis, and mouse models to investigate how disruptions in the circadian rhythm of glucocorticoids (referred to as glucocorticoid flattening) initiates multi-organ signal changes in the liver, pancreatic islets, muscle and fat. The most remarkable signal changes is a greatly increased insulin release from beta cells even when glucose levels are low, and a parallel loss of muscle loss and greatly increased fat mass. Markedly, we find that disrupting these glucocorticoid rhythms increases fat mass to a similar degree but through independent molecular mechanisms from the well-studied effects of high fat diet and excessive calorie intake. I will show initial findings of molecular mechanisms causing the fat mass increase and present conceptual ideas how to understand the multi-organ signaling process controlling the two types of obesity. Our findings open-up new possibilities for developing personalized strategies to treat obesity caused by stress and sleep deprivation.

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MS162

Modeling Type 2 Diabetes Progression: Looking Beyond the Iceberg of Data

Mathematical modeling is a powerful quantitative tool to investigate the pathogenesis of type 2 diabetes (T2D). Leveraging a four-dimensional longitudinal dataset from Southwest Native Americans who progressed from normal glucose tolerance to T2D, we developed twenty mathematical models, starting with a minimally modified version of the classic Topp model and iteratively incorporating additional model elements to account for new biological mechanisms until optimal data fit was achieved. The notable variability of the individual trajectories was overcome by the non-linear mixed-effect modeling approach. Despite the absence of a discernible common trend among the individual trajectories of each variable, the optimal model effectively captured the diverse glucose-insulin dynamics of individuals progressing to T2D. The reliability of the model was reinforced by its successful cross-validation against a subset of individuals progressing only to prediabetes. The model was then applied to address controversial questions related to the role of insulin hypersecretion in disease progression.

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MS163

A Lagrangian-Eulerian Multiscale Data Assimilation Framework

Lagrangian trajectories are widely used as observations to recover the underlying flow field via Lagrangian data assimilation (DA). However, the strong nonlinearity in the observational process and the high dimensionality of the problems often cause challenges in applying standard Lagrangian DA. In this paper, a Lagrangian-Eulerian multiscale DA (LEMDA) framework is developed. It starts by exploiting the Boltzmann kinetic description of particle dynamics to derive a set of continuum equations, which characterize the statistical quantities of particle motions at fixed grids and serve as Eulerian observations. Despite the nonlinearity in the continuum equations and the processes of Lagrangian observations, the time evolutions of the posterior distribution from LEMDA can be written down using closed analytic formulae. This offers an exact and efficient way of carrying out DA, which avoids using ensemble approximations and the associated tunings. The Lagrangian DA has advantages when a moderate number of particles is used, while the Eulerian DA can effectively save computational costs when the number of particle observations becomes large. The Eulerian DA is also valuable when particles collide, such as using sea ice floe trajectories as observations. LEMDA naturally applies to multiscale turbulent flow fields, where the Eulerian DA recovers the large-scale structures, and the Lagrangian DA efficiently resolves the small-scale features in each grid cell via parallel computing.

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MS163

Data-Driven Parameter Estimation in a Reduced-Order Quasi-Geostrophic Model of the Polar Vortex Using Ensemble Smoothing with Multiple Data Assimilation

Parameter estimation is fundamental to understanding complex dynamical systems, particularly in climate science where reduced-order models help capture essential physical mechanisms. In this talk, we explore the application of Ensemble Smoothing with Multiple Data Assimilation (ESMDA) methods to improve the estimation of time-dependent parameters in stratospheric dynamics. We examine a reduced-order model (Ruzmaikin et al., 2003) that describes wave-zonal interactions in the stratosphere, employing ESMDA to assimilate 20 years of ECMWF atmospheric reanalysis data. Our focus is on estimating two key parameters: Λ, representing the vertical gradient of the mean radiative zonal wind, and h, a perturbation parameter reflecting the impact of upward-propagating Rossby waves from the troposphere. We will explore the essential parameter properties required to match the reanalysis data and highlight physical signatures within the parameter estimates around known Sudden Stratospheric Warming (SSW) events. By assimilating observational data into these modeling frameworks, we aim to refine parameter estimates, reducing uncertainties and enhancing our understanding of stratospheric circulation dynamics.

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MS163

Covariance Estimation for High-Dimensional Data Assimilation Applications

Covariance estimation is a fundamental task in statistics and is a key step in many algorithms for uncertainty quantification, machine learning, and data assimilation. In applications, such as geophysical data assimilation, where state spaces are high-dimensional and sample sizes are often small, covariance estimation is challenging. The sample covariance is known to be a poor estimator, and though several estimation techniques have been proposed to address this issue, algorithms, such as the ensemble Kalman filter (EnKF), can be sensitive to these covariance estimates. In this talk, we review a variety of different covariance estimation techniques for high-dimensional, low sample size problems, compiling various methods form across statistics and and geoscience. In our review, we perform a comparative study of these methods for covariance estimation in an EnKF. We present results from two sets of experiments: the first applies an EnKF for joint state-parameter estimation with a Lorenz 96 model, and the second applies an EnKF for state estimation in a two-layer, two space dimensional quasi-geostrophic model. We discuss how each method relies on a different set of assumptions, which in turn defines their applicability, scalability, and practicality for data assimilation and other high-dimensional covariance estimation applications. In addition, we introduce a new method of covariance that tapering incorporates dynamical considerations into its construction.

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MS163

Adaptive Localisation for Iterative Ensemble Smoothers in a Coupled Multiscale Model

With a coupled nonlinear, unstable dynamical system consisting of two Kuramoto-Sivashinsky equations, we demonstrate the effectiveness of ensemble smoothers, originally developed in petroleum engineering. By using localisation, the assilimation improves the estimates of the different spatial and temporal scales of the two subsystems of an earth-system model. An evaluation of the cross-covariance between their variables supports the choices we make in the setup of the localisation scheme. Localization effectively reduces the impact of spurious correlations, thereby improving data assimilation efficiency with a relatively small ensemble. We compare the commonly used distance-based localization with so-called adaptive correlation-based localization that adapts the localization to correlations between model variables and observations to correlation-based distances, instead of physical distances. We evaluate their effectiveness for different implementations, providing detailed explanations for the observed performance differences, including the influence of data gaps in one system on the other. Based on our results, we present the possibilities and benefits of implementing this approach in coupled earth-system models.

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MS164

Attractor Sheaves: Computing Sheaf Cohomology for the Detection of Bifurcations

Algebraic structures such as lattices of attractors and Morse decompositions provide a computable description of global dynamics. For parameterized families of dynamical systems, these structures form a sheaf over the parameter space. Sheaf cohomology provides information about the global sections of the attractor sheaf and changes in this structure that detect bifurcations.

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MS164

Measuring Resilience of Dynamic Structures Via Transient Dynamics

Classical topological definitions of dynamic structures such as attractors, repellers, and Morse sets lack metric information relevant to measuring resilience in real-world systems. To understand resilience, we would like to know not just whether structures persist in the face of sufficiently small perturbations but *how small* is small enough. In this talk we present a partial solution to this problem, which we call intensity of attraction. Intensity generalizes the resilience metric of basin slope [Beisner et al., Alternative stable states in ecology, Front. Ecol. Environ. 1(7), 376382, 2003] to autonomous ODE models in arbitrary dimension. One can compute an attractors intensity by probing a domain of attraction with bounded, non-autonomous control and tracking the sets reachable from the attractor. A connection between reachable sets and isolating blocks implies that an attractors intensity not only reflects its capacity to retain solutions under time-varying perturbations, but also gives a lower bound on the distance the attractor continues in the space of vector field functions. We will illustrate attractor intensity in the context of a population model and discuss prospects for generalizing the theory to repellers and Morse sets.

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MS164

Analyzing Dynamical Changes of Noisy Spatial Population Time Series Using Persistent Homology

Natural systems worldwide are experiencing decline due to climate change and increasing human pressure. Here, we seek to predict impending change in spatially distributed populations by quantifying changes in spatial distribution patterns during a dynamical change (such as an extinction event). We use computational topology, and more specifically, persistent cubical homology for pattern quantification. As real-world data inevitably always contains error and/or noise, we also perform image processing on noisy spatial distribution patterns. Preliminary results show that certain image processing procedures are capable of destroying noise while retaining topological information about the spatial patterns, and we can observe topological early warning signals of population collapse.

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MS164

Persistence of Morse Decompositions over Numerical Resolution

The dynamical properties of a continuous self-map of a compact metric space depend on the resolution at which we study them. In general, more points exhibit recurrent behavior as the resolution becomes coarser. We can measure this dependence using persistence, a technique from topological data analysis. We show how persistence can apply to a Morse decomposition of the dynamics into recurrent and gradient-like pieces, which gives both local and global information.

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MS165

Turbulence via Intermolecular Potential

I will present a novel theory of spontaneous development of turbulence in gases at low Mach numbers, which is consistent with observations. According to my theory, at low Mach numbers, the pressure variable is damped via the imbalance between the incident and recedent pairs of molecules in the pair correlation function of the Vlasov collision integral. The aforementioned imbalance occurs due to compression or expansion of the gas (if the gas is compressing, there are more incident pairs than recedent, and vice versa). As a result, the van der Waals effect becomes non-negligible under the pressure gradient in the momentum transport equation, and couples the density and the divergence of velocity into a linearly unstable, chaotic, rapidly oscillating system. In turn, this chaotic density-divergence system produces turbulent dynamics by exponentially amplifying small noisy fluctuations around a laminar flow. I will also show animations of a numerically simulated turbulent flow, which look visually similar to observations and experiments.

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MS165

High-Amplitude Stokes Waves in a Fluid of Fixed Finite Depth.

We apply a Newton-conjugate residual method to the conformal formulation of the one-dimensional Euler Water Wave Problem in terms of the horizontal spatial variable x and the vertical spatial variable y to find Stokes waves in a particular conformal depth. We then find Stokes waves traveling in a fluid of a fixed physical depth through the use of a root-finding method. We compute the poles of these waves viewed as a function of the complex variable $z = x + iy$, identify any bifurcation points that occur as these wave increase in amplitude, and analyze the evolution of various physical quantities (energy, speed, steepness) as a function of amplitude through the lens of the infinite-depth asymptotic analysis done by Longuett-Higgins and Fox. Finally, we compute how the the stability specta of these waves evolves as we increase steepness.

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MS165

Singularities in Conformal Plane for 2D Fluid

We consider the classical problem of 2D fluid flow with a free boundary. Recent works strongly suggest that square–root type branch points appear naturally in 2D hydrodynamics. We illustrate how the fluid domain can be complemented by a “virtual’ fluid, and the equations of motion are transplanted to a branch cut (a vortex sheet) in the conformal domain. A numerical and theoretical study of the motion of complex singularities in multiple Riemann sheets is suggested. Unlike preceding work for dynamics of singularities: the short branch cut approximation, and the study of viability of meromorphic solutions in fluid dynamics, the present approach neither simplifies the equations of fluid flow, nor uses local Laurent expansions. Instead the new approach is based on analytic functions and allows construction of global solutions in 2D hydrodynamics. A natural extension of the approach considers fluid flows described by many pairs of square–root branch points.

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MS165

Exact Solution and Integrability of Ballistic Motion of Fluid with Free Surface

A fully nonlinear dynamics for potential flow of ideal incompressible fluid with a free surface is considered in two dimensional geometry. A fluid is assumed to be moving at large distances either towards or away from the origin which can be considered as a version of ballistic motion. An infinite set of exact solution is found including formation of droplets and cusps on a free surface. These solutions are characterized by motion of complex singularities outside of fluid and can be obtained from fully integrable exact reductions of fluid dynamics.

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MS166

Dynamics of a Vibro-Impact Energy Harvester with Dry Friction

Vibro-impact (VI) systems are nonlinear systems that are used in many engineering applications, such as energy harvesting (EH). In this talk, we present a VI system that consists of an externally forced inclined cylindrical capsule and a bullet that is allowed to freely move inside the capsule. Dry friction between the capsule and the bullet is taken into account, and may result in sliding motion between impacts. The ends of the capsule are covered with dielectric elastomer membranes, resulting in a differential in electrical output that can be harvested at impacts between the bullet and membranes. Parametric studies, including numerical and analytical tools, reveal an interplay of smooth and non-smooth bifurcations of (ir)regular impact sequences, including grazing bifurcations, leading to additional low-velocity impacts. These grazing bifurcations can be delayed due to sliding bifurcation, and sustain higher energy output states. Here, we focus on the interplay between dry friction, forcing frequency, and noise, on the dynamics and energy performance of the VI-EH device.

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MS166

Vibro-Impact Energy Harvesting Via Computer-Assisted Analysis

In this talk, we present a novel approach for studying the global dynamics of a vibro-impact pair, that is, a ball moving in a harmonically forced capsule and deforming top and bottom membranes on the capsule ends. Motivated by a specific context of vibro-impact energy harvesting, we develop the method with broader non-smooth systems in mind. We exploit the impacts as useful non-smooth features to select appropriate return maps that give a path for studying global behavior. This choice yields a computationally efficient framework for constructing return maps on short-time realizations from the state space of possible initial conditions rather than via long-time simulations often used to generate more traditional maps. We extend the results of our previous work [Bao at al., SIADS, 2025] on characterizing global properties of 1:1 periodic bottom-top-bottom (BTB) motion to richer 2:1 type periodic motion, using a longer bottom-top-bottom-bottom (BTBB)/bottom-bottom-top-bottom (BBTB) sequencies in the first return map. This study provides new insights into the global dynamics of energetically favorable states and illustrates the potential of this approach in broader classes of dynamics.

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MS166

Some Nonsmooth Bifurcation Problems in Impacting Mechanical Systems

Piecewise-smooth dynamical systems, with continuous time, can be categorised into a number of different classes depending on the degree of discontinuity across each switching surface. Perhaps the harshest systems are impacting systems, where at a discontinuity there is an O(1) change in the system state. Examples of such systems are common in mechanical systems with hard constraints. Here I shall give an overview of some recent results including on local generation of oscillations at boundary equilibrium bifurcations and the Painleve paradox of loss of determinism when combining impact with friction. Applications touched upon will include: the origin of limit-cycle oscillation of aircraft flaps with freeplay; a novel approach to suppression of pressure-relieve-valve instability; and an explanation of why you call pull chalk across a chalkboard, but not push it.

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MS166

Geometric Constructions and Computer-Assisted Proofs of Chaos for Piecewise-Smooth Maps

Trapping regions and invariant expanding cones have long been used as geometric tools for establishing the presence of a chaotic attractor, but it is perhaps under appreciated that these work brilliantly for piecewise-linear maps. Immediately they show the chaos is robust to parameters, and they can be constructed explicitly and in some cases so simply that parameter combinations at which the construction fails correspond exactly to bifurcations where the chaos is actually lost. More complex constructions based on higher iterates can be done computationally, and this leads to computer-assisted proofs of chaos. The results show that power converters used widely in electronics can operate chaotically over intervals of parameter values immediately beyond border-collision bifurcations.

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MS167

Quantum Simulation of Nonlinear Dynamics Using Repeated Measurement

We present a quantum algorithm based on repeated measurement to solve initial-value nonlinear ordinary differential equations (ODEs). The algorithm relies on classical evaluation of a summation over sub-Hamiltonians, weighted by the expectation values of paired observables. Standard quantum Hamiltonian simulation bridges the short times between evaluation of new Hamiltonian matrices. This algorithm requires an ensemble of quantum states, where each step consumes a subset of quantum states, which are used for measurements and are discarded from further time advance. We apply this approach to the classic logistic and Lorenz systems, in both integrable and chaotic regimes. After demonstrating that our algorithm is capable of solving nontrivial problems, we explore the question of efficiency: For what class of problems is the algorithm efficient? For a range of problem classes, we use classical simulations to estimate how algorithmic errors scale with simulation time. We present potential physical systems for the problem classes, providing further analytical analysis.

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MS167

Modeling Classical Data with Quantum Computers

While quantum computers are not yet able to execute large fault tolerant algorithms, the steady increase in qubit count and gate fidelity across several quantum hardware platforms makes it possible to design and test increasingly sophisticated heuristic algorithms which leverage both quantum and classical resources. In this talk, we will discuss the application of these hybrid techniques in modeling classical data. We will first discuss state preparation, which in this context involves loading data into a quantum state and is a necessary first step of many quantum algorithms. We will discuss how different data embeddings influence the expressivity of quantum models, and focus on a novel approach for achieving efficient data representation via techniques that convert matrix product states to quantum circuits. We will present experimental results for up to 20 qubits for two applications of this technique - loading normal distributions, and loading image data. Further, we will discuss how to design and efficiently train variational quantum ansatzes that can be used to model correlations in the dataset, including examples from both discriminative and generative learning. We thus show how it may be possible for quantum computers to be utilized for practical data modeling applications even before fully fault tolerant quantum computers are available.

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MS167

Fock Space Kernel Embeddings of Dynamical Systems

Given a measure preserving dynamical system (X, Φ) we consider a spectral approximation of the associated Koopman operator. By taking a weighted Fock space amplification of this approximate Koopman operator we obtain an embedding of X into a high dimensional space B. B is also equipped with a rotation system dynamic and a reproducing kernel Hilbert space. Under this rotation system dynamic B has many preserved subspaces, $Y \subset B$. In this talk we present evidence that the original Koopman can be well approximated by the interpolation to X of evolved observables on one of these preserved subspaces Y.

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MS167

Quantum Mechanical Closure of Parametrized

Shallow Water Dynamics

The closure of parametrized dynamical systems involves the definition and use of a surrogate model to determine the fluxes from the unresolved degrees of freedom needed for timestepping the resolved system state. In this work, we employ a data driven closure scheme based on the mathematical framework of quantum mechanics and Koopman operator theory, where the surrogate system is cast as a time dependent quantum state. We apply this scheme to a parametrized version of the shallow water equations on a periodic domain, where the resolved variables are defined as local spatial averages over finite volume cells. We present numerical results demonstrating the effectiveness of the closure scheme in accurately reproducing the spatiotemporal dynamics for several tested initial conditions.

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MS168

Unlocking the Broadband Response of Jump-Induced Nonlinear Dynamics in High-Dimension

This talk introduces a novel stochastic framework aimed at enhancing the solutions realism by enriching their temporal variability, for high-dimensional systems characterized by a fundamental, nonlinear oscillation. By leveraging the concept of isochronslevel sets of the oscillation's phase functionwe identify the key underlying nonlinear mechanisms governing the systems response to stochastic disturbances. This understanding empowers us to systematically develop analytical formulas for stochastic parameterizations that model unresolved physics as phase-dependent, jump-diffusion processes. Our approach effectively induces complexity, transforming the unperturbed periodic dynamics into stochastic chaotic solutions with novel characteristics. This complexity is characterized by a broadband spectral response and associated with complex stochastic pullback attractors in high-dimensional spaces. We will delve into new insights regarding the types of stochastic chaos that can emerge from this framework. To illustrate the theory, we will present applications to ENSO theory and cloud physics. Specifically, we will demonstrate how our framework can be successfully applied to conceptual cloud-rain models with delays, reproducing the intricate temporal variability of open-cell oscillations observed in high-fidelity simulations of marine stratocumulus clouds.

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MS168

Data-Driven Reduction to Spectral Submanifolds for Neural Network Models

In many fields of applied science and engineering, recurrent neural networks (RNNs) or neural ordinary differential equations(neural ODEs) are trained to reproduce the behavior of a set of observables of high-dimensional dynamical systems. These RNNs and neural ODEs, however, are often high dimensional and hence the dynamics they generate are poorly understood. Here we use the theory of spectral submanifolds (SSMs) to reduce high-dimensional neural ODEs or RNNs models to very low-dimensional attracting invariant manifolds in their phase spaces. Since the manifolds and the reduced-order models we find are structurally stable, we can also predict the dynamics under parameter changes and time dependence, with the latter including random time dependence that models noise. We illustrate this SSM-based neural net reduction approach on several examples taken from the literature.

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MS168

Some Nonautonomous Bifurcation and Critical Transitions Results for Concave-convex Scalar ODEs

A mathematical modeling process for phenomena with a single state variable that attempts to be realistic must be given by a scalar nonautonomous differential equation $x' = f(t,x)$ that is concave with respect to the state variable x in some regions of its domain and convex in the complementary zones. This work takes the first step towards developing a theory intended to describe the corresponding dynamics: the case in which f is concave on the region $x \geq b(t)$ and convex on $x \leq b(t)$, where b is a C^1 map, is considered. The different long-term dynamics that may appear are analyzed while describing the bifurcation diagram for $x' = f(t,x) + \lambda$. The results are used to establish conditions on a concave-convex map h and a nonnegative map k ensuring the existence of a value ρ_0 giving rise to the unique critical transition for the parametric family of equations $x' = h(t,x) - \rho\, k(t,x)$, which is assumed to approach $x' = h(t,x)$ as time decreases, but for which no conditions are assumed on the future dynamics. The developed theory is applied to describe a population dynamics model for which a large enough increase on the peak of a temporary higher predation causes extinction.

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MS168

A Numerical Method for Measuring Dynamical Phase Transitions in Non-Autonomous Systems

The quantitative identification of chaos in non-autonomous dynamical systems is a non-trivial task, as one cannot rely on time-averaging methods. To address this challenge, ensemble simulations have been introduced, allowing for the generalization of the classical Lyapunov exponent to an instantaneous one [Jnosi et al., Physics Reports 1092, 164 (2024)]. Alternatively, entropy-like quantities can also be used to identify chaos in non-autonomous dynamics. Using ensemble simulations, we generalize a recently introduced method for measuring dynamical phase transitions in the order-q Rnyi entropy [Sndor et al., arXiv:2407.13452 (2024)] to systems with a drifting parameter. By applying an appropriate symbolization technique at discrete time steps, symbols can be assigned to all elements of the ensemble. Based on transitions between these symbols in consecutive steps, an approximate Markov process model of the dynamics can be constructed, and the derivative of the Rnyi entropy at q=1, termed here the Lyapunov measure, can be computed directly from the transition probability matrix (see reference above). We find that the Lyapunov measure for a non-autonomous system with drifting parameter exhibits pronounced peaks whenever the system transitions through periodic windows corresponding to the frozen parameter setup, thus providing evidence of dynamical phase transitions.

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MS169

Bistability of the Large-Scale Tropical Circulation

The existence of tipping points, i.e. bifurcations potentially leading to abrupt climate change, remains a major source of uncertainty for climate projections for the coming centuries. Paleoclimate records suggest that such events have occurred in Earths past, on timescales which do not exceed a decade. Yet, it remains unclear whether the large-scale atmospheric circulation, which is the fastest component of the climate system, may undergo such transitions. In this talk I will discuss the possibility of bifurcations of the circulation of the tropical atmosphere: specifically, the reversal of the mean zonal winds (a phenomenon known as superrotation) and the collapse of the meridional circulation (Hadley cell). I will discuss theoretical mechanisms, based in particular on Rossby wave resonance, and their relevance for the Earth using numerical simulations across a hierarchy of models of increasing complexity. I will also present some results indicating that a transition to superrotation might strongly affect the water cycle, and, through radiative feedbacks, surface temperature.

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MS169

Balanced Asymptotic Models for the Earth's Troposphere

Asymptotic methods have been widely used in theoretical meteorology to obtain simplified and easily interpretable models. The aim of the study was to build a global asymptotic model valid at large scales (bigger than 500km), for the entire atmosphere. Three balanced models, valid for the tropics, subtropics and the midlatitudes have been obtained and the technique of matched asymptotics has been used to get matching conditions between the solutions. The non-dimensionalised tropical model of Majda Biello(2012) has been used as the starting point. Using scaling arguments, we have determined the latitudinal extent of the tropical model and derived a new balanced model valid for the subtropics. The temperature stratification at the equator emerges as a matching condition between the leading order tropical and subtropical solutions. The scaling of the next order subtropical solution was used to obtain the third model valid for planetary scales in the midlatitudes. The tropical and subtropical models act as boundary layers while the planetary scale midlatitude model acts as the outer layer.

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MS169

Traveling Spatially Localized Convective Structures in An Inclined Porous Medium

Stationary, localized structures were recently found for inclined porous medium convection with constant-temperature boundaries. We analyze drifting asymmetric, localized convective structures consisting of one to five pulses in a 2D inclined porous layer with a fixed bottom temperature and an imperfectly conducting top boundary, breaking midplane reflection symmetry. Direct numerical simulations (DNS) show pulse drift speed c varies with the symmetry-breaking parameter $\kappa \geq 0$ based on the Biot number, with $c = 0$ at $\kappa = 0$ (symmetric case). $c > 0$ (upslope) rises monotonically with κ in small domains;c changes sign based on parameters in large domains. Pulse tails, controlling interactions, rely on the dominant spatial eigenvalues, with a transition at $\kappa_c > 0$: below κ_c, dominant eigenvalues are complex, producing oscillatory tails; above κ_c, one dominant spatial eigenvalue turns real, producing a monotonic downslope tail. Below κ_c, traveling bound states with multiple pulses exist, whose collisions are studied. Well above κ_c, pulses repel and spread equidistantly in the domain. A reduced model, based on tail interaction, reproduces repulsion and collisions from DNS. Transition to equidistant spreading occurs when monotonic/oscillatory tails have equal slope. This study elucidates the motion of localized patterns in moderate-Rayleigh number convection in an inclined porous layer with an imperfectly conducting boundary.

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MS169

Morphologies of Rotating Moist Convection

Moist convection is a process which occurs in planetary atmospheres whereby the latent heat released by condensation triggers overturning convection when the temperature gradient would otherwise be stable. This leads to an up-down asymmetry and an inhomogeneous heat source driving the convective flows. Due to this inhomogeneity, moist convection may respond strongly to changes in flow morphology such as those induced by rotation. To investigate, we run a suite of 3D simulations of rotating moist convection using the Rainy-Benard model of Vallis et al. 2019 where we vary rotation rate and Rayleigh number. We identify three different dynamical regimes, cellular flows, funnel-like cells with an inner spiral core, and plumes. We characterize where these regimes exist in parameter space. We also report heat transport scalings and discuss how this is effected by the different dynamical regimes as well as the implications for the dynamics of planetary atmospheres.

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MS170

Dynamics of Adaptive Contact Processes

Adaptive networks provide a remarkable flexibility in modelling a wide variety of complex systems. Yet, they also show many additional phenomena that arise once a static network is turned into an adaptive one. I am going to follow this theme in my talk and present several phenomena in adaptive networks for contact process-type dynamics such as epidemic spreading and opinion formation. This will include not only changes in the type of bifurcations and phenomena observed but we will also look at finer technical details such as convergence rates to equilibrium and refinements of moment closure techniques to study mean-field dynamics.

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MS170

Mean Field Limits of Adaptive Signed Heterogeneous Networks

Adaptive dynamical networks are used to model interacting particle systems with time-varying connections among particles. In this talk, I will introduce our results on mean field limits of an adaptive signed heterogeneous Kuramoto network. The mean field limits are given by weak solutions to an implicit PDE, the so-called generalized Vlasov equation. We provide the well-posedness and approximation of the mean field limits. The results rely on the approximation of signed-measure-valued functions as graph limits as well as a variation of parameters formula for measure-valued integral equations. The approach seems to apply to other dynamical systems coupled on large signed graphs that coevolve with the nodal dynamical systems. This is a joint work with Marios Antonios Gkogkas and Christian Kuehn.

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MS170

Recurrent Chaotic Clustering and Slow Chaos in Adaptive Networks

Adaptive dynamical networks are network systems in which the structure co-evolves and interacts with the dynamical state of the nodes. We study an adaptive dynamical network in which the structure changes on a slower time scale relative to the fast dynamics of the nodes. We identify a phenomenon we refer to as recurrent adaptive chaotic clustering, in which chaos is observed on a slow time scale, while the fast time scale exhibits regular dynamics. Such slow chaos is further characterized by long (relative to the fast time scale) regimes of frequency clusters or frequency-synchronized dynamics, interrupted by fast jumps between these regimes. We also determine parameter values where the time intervals between jumps are chaotic and show that such a state is robust to changes in parameters and initial conditions.

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MS171

Koopmanism in Climate Science

The majority of dynamical systems arising from applications show a chaotic character. This is especially true for climate and weather applications. We present here an application of the Koopman operators method to tropical and global SST that yields an approximation to the continuous spectrum typical of these situations. Traditionally, climate variability analysis has relied on linear techniques such as Principal Component Analysis (PCA) and linear instability theory, which capture dominant modes but may miss nonlinear dynamical features critical to understanding complex climate behavior. A difference with other analysis method, as EOF or Fourier expansion, is the the Koopman modes have a dynamical interpretation thanks to their connection to the Koopman operator and they are not constrained in their shape by special requirements as orthogonality (as it is the case for EOF) or pure periodicity (as in the case of Fourier expansion). The pure periodic modes emerge naturally and they form a subspace that can be interpreted as the limiting subspace for the variability. The stationary states therefore are the scaffolding around which the dynamics takes place.

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MS171

Koopman Learning with Episodic Memory

Koopman operator theory has found significant success in learning models of complex, real-world dynamical systems, enabling prediction and control. The greater interpretability and lower computational costs of these models, compared to traditional machine learning methodologies, make Koopman learning an especially appealing approach. Despite this, little work has been performed on endowing Koopman learning with the ability to leverage its own failures. To address this, we equip Koopman methods - developed for predicting non-autonomous time-series - with an episodic memory mechanism, enabling global recall of (or attention to) periods in time where similar dynamics previously occurred. We find that a basic implementation of Koopman learning with episodic memory leads to significant improvements in prediction on synthetic and real-world data. Our framework has considerable potential for expansion, allowing for future advances, and opens exciting new directions for Koopman learning.

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MS171

Trading Curse of Dimensionality with Complexity in Hamilton Jacobi Solution Using Koopman Spectrum

We discover the spectral Koopman Hopf formula for solving Hamilton Jacobi equation that arise in class of optimal control problems with control-affine dynamics. The Hopf formula provides a state space parallelizable optimization-based solution for the computation of optimal value function. However, this formula only applies to optimal control problems where the underlying Hamiltonian is state-independent. The state-independent Hamiltonian severely restricts the applicability of the Hopf formula. We extend the applicability of the Hopf formula to the general class of control-affine nonlinear systems where the Hamiltonian function is not state-independent. We use spectral properties of the Koopman operator associated with the uncontrolled system to transform the state-dependent Hamiltonian to a state-independent one. The attractive feature of the Hopf formula is it transforms the curse of dimensionality problem associated with solving the Hamilton Jacobi equation to the so-called curse of complexity problem. We show that the proposed spectral Koopman Hopf formula also does not suffer from the curse of dimensionality, thereby preserving the complexity of the Hopf formula. This preservation of complexity is made possible by proposing the use of path-integral formula for the computation of Koopman principal eigenfunctions. We provide necessary and sufficient conditions for the applicability of path-integral formula and present simulation results to verify the developed framework.

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MS171

Koopman Learning with State Functions Versus Projected Representations

The Koopman operator of a dynamic process is a powerful representation: it enables visualization of the spectra and the modes of a dynamic system and more broadly, linearization of nonlinear dynamics to apply established methods in control, analysis, and optimization. In data oriented applications, a system with often unknown physics is represented entirely by data, often high-dimensional in nature. Thus, it is often desirable or requisite to perform some form of dimensionality reduction or projection on the data. We examine the physical and structural implications of data projection on learned Koopman operator representations, through the standard approach of finding embeddings, as well as through other projection methods that rely on partitioning of measured features from latent features and their implications on system structure. Certain aspects of network structure are obscured, as certain dependencies are encoded by nonlinear structure. Thus, while a Koopman operator model may exhibit high model fidelity from a state-to-output perspective or an input-to-output perspective, it may not necessarily capture system structure or physical dependency. We illustrate these concepts with two simple examples from biology and networked systems.

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MS172

Timescales of Tipping Cascades

Climate tipping elements are large-scale subsystems of the Earth that may transgress critical thresholds (tipping points) under ongoing global warming, with substantial impacts on the biosphere and human societies. While many of these systems have been studied in isolation, it is yet largely unknown how they may interact and affect each others tipping behaviour. For example, an AMOC collapse could redistribute rainfall across the Amazon and thereby affect its internal forest-rainfall feedback. One of the most feared scenarios is that the tipping of one element might cause another elements to tip as well – a phenomena that is called a tipping cascade. In this talk, we will use conceptual models to study tipping cascades between two uni-directionally coupled systems that each have a distinct internal time scale, making it a non-autonomous fast-slow system. We will use this model to distinguish between cascading and non-cascading tipping, and explore the usefulness of early warning signs in these contexts.

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MS172

Cancer Model with Moving Extinction Threshold Reproduces Real Cancer Data

We propose a simple dynamic model of cancer development that captures carcinogenesis and subsequent cancer progression. A central idea of the model is to include the immune system as an extinction threshold, similar to the strong Allee effect in population biology. We first identify the limitations of commonly used Allee effect models in reproducing typical cancer progression. We then address these limitations by deriving a new model that incorporates: (i) random mutations of stem cells at a rate that increases with age and (ii) immune response whose strength may also vary over time. Our model accurately reproduces a wide range of real-world cancer data: the progression of breast cancer in mice, the typical age-specific cumulative risk of most human cancers, and the unusual age-specific cumulative risk of breast cancer in women. In the last case, we use a moving extinction threshold to reflect the different immune response at different phases of the menstrual cycle and menopausal treatment. This provides new insights into the effects of hormone replacement therapy and menstrual cycle length. This moving threshold approach can be applied to a variety of other cancer scenarios where the immune response or other parameters may vary over time.

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MS172

Quantifying Tipping Behaviour: Geometric Early Warnings and Quasipotentials for a Box Model of the AMOC

A non-autonomous system can undergo a rapid change of state in response to a small or slow change in forcing, due to the presence of nonlinear processes that give rise to critical transitions or tipping points. Such transitions are thought possible in various subsystems (tipping elements) of the Earth's climate system. The Atlantic Meridional Overturning Circulation (AMOC) is considered a particular tipping element where models of varying complexity have shown the potential for bi-stability and tipping. We consider both transient and stochastic forcing of a simple but data-adapted model of the AMOC. We propose and test a geometric early warning signal to predict whether tipping will occur for large transient forcing, based on the dynamics near an edge state. For stochastic forcing, we quantify mean times between noise-induced tipping in the presence of stochastic forcing using an Ordered Line Integral Method (OLIM) of Cameron (2018) to estimate the quasipotential. We calculate minimum action paths (MAPs) between stable states for various scenarios. Finally, we discuss the problem of finding early warnings in the presence of both transient and stochastic forcing.

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MS172

Tipping of the Atlantic Ocean Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the climate system because of its role in the global meridional heat transport. Paleoclimate records as well as a hierarchy of climate models have indicated that the AMOC is a tipping element, which can undergo a transition to a collapsed state due to its sensitivity to changes in buoyancy forcing. The decadal-to-centennial time scale climate impacts of such a transition are disruptive and are possibly beyond what can be handled by society through adaptation measures. A central issue is to determine the probability that the AMOC will start to collapse before the year 2100. In this presentation, I will describe the efforts so far to tackle this issue using Large Deviation Theory and (numerical) rare-event techniques such as Adaptive Multilevel Sampling. Results will be illustrated using a hierarchy of AMOC models, from conceptual box models to spatially extended ocean models.

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MS173

Controllability and Observability of Hypergraph Dynamics

In this talk we discuss aspects of the dynamics and control of dynamical systems on hypergraphs. We contrast such dynamics with dynamics on graphs and discuss how polynomial nonlinearities naturally arise. We then apply the tool of nonlinear control theory to analyze the controllability and observability of such systems. Examples in biology and other areas will be given.

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MS173

Insights from Exact Social Contagion Dynamics on Networks with Higher-Order Structures

Recently there has been an increasing interest in studying dynamical processes on networks exhibiting higher-order structures, such as simplicial complexes, where the dynamics acts above and beyond dyadic interactions. Using simulations or heuristically derived epidemic spreading models it was shown that new phenomena can emerge, such as bi-stability/multistability. Here, we show that such new emerging phenomena do not require complex contact patterns, such as community structures, but naturally result from the higher-order contagion mechanisms. We show this by deriving an exact higher-order SIS model and its limiting mean-field equivalent for fully connected simplicial complexes. Going beyond previous results, we also give the global bifurcation picture for networks with 3- and 4-body interactions, with the latter allowing for two non-trivial stable endemic steady states. Differently from previous approaches, we are able to study systems featuring interactions of arbitrary order. In addition, we characterise the contributions from higher-order infections to the endemic equilibrium as perturbations of the pairwise baseline, finding that these diminish as the pairwise rate of infection increases. Our approach represents a first step towards a principled understanding of higher-order contagion processes beyond triads and opens up further directions for analytical investigations.

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MS173

Opinion Disparity in Hypergraphs with Community Structure: Theory and Practice

The division of a social group into subgroups with opposing opinions, which we refer to as *opinion disparity*, is a prevalent phenomenon in society. This phenomenon has been modeled by including mechanisms such as opinion homophily, bounded confidence interactions, and social reinforcement mechanisms. We present a complementary mechanism for the formation of opinion disparity based on higher-order interactions, i.e., simultaneous interactions between multiple agents. We present an extension of the planted partition model for uniform hypergraphs as a simple model of community structure, and we consider the hypergraph Susceptible-Infected-Susceptible (SIS) model on a hypergraph with two communities where the binary ideology can spread via links (pairwise interactions) and triangles (three-way interactions). We approximate this contagion process with a mean-field model and find that for strong enough community structure, the two communities can hold very different average opinions. We determine the regimes of structural and infectious parameters for which this opinion disparity can exist, and we find that the existence of these disparities is much more sensitive to the triangle community structure than to the link community structure. Lastly, we discuss the algorithmic considerations when numerically validating these analytical results.

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MS173

Sync with Higher-Order Interactions: Effects on Basins and Linear Stability

Higher-order interactions, through which three or more entities interact simultaneously, are crucial for faithfully modeling many real-world complex systems. A key challenge in nonlinear dynamics and network science is understanding how these higher-order interactions influence collective dynamics. Here, we examine their effects from both local and global perspectives. First, from a local perspective, we show numerically and analytically that hyperedges typically enhance the linear stability of synchronization in random hypergraphs but have the opposite effect in simplicial complexes. We identify higher-order degree heterogeneity as the key structural determinant of synchronization stability in systems with a fixed coupling budget. This demonstrates that higher-order interactions do not always stabilize synchronization, even locally. Second, adopting a global viewpoint, we investigate the basins of attraction of synchronized states and how higher-order interactions affect them. We show that the basins of synchronized states (such as full synchrony and twisted states) often shrink dramatically as stronger higher-order interactions are included. This occurs even though the linear stability of these states increases, resulting in basins that become "deeper but smaller," making it unlikely for random initial conditions to reach them. Our results highlight the importance of understanding higher-order interactions from both local and global perspectives

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MS174

Distributed and Adversarial Training of Large Machine Learning Models

Optimization has played an essential role in machine learning by providing a conceptual and practical framework on which algorithms, systems, and datasets were brought together at unprecedented scales. However, recent developments towards even larger models with billions of parameters pose new challenges for optimization and new opportunities for cross-fertilization between theory and practice. My talk will highlight this cross-fertilization on two examples related to distributed and adversarial training. I will highlight how foundation models such as RoBERTa can be vulnerable to adversarial label poisoning and introduce a robust training algorithm that solves a bilevel optimization problem to address this vulnerability. The second part of the talk introduces an event-based communication protocol for distributed training that has strong convergence guarantees (acceleration and robustness to non-i.i.d. data), can be applied to distributed optimization problems over graphs, and achieves a better communication vs. accuracy trade-off than federated learning algorithms (e.g., federated averaging or FedProx).

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MS174

Modelling the Non-Stationarity of Capacity in Neural Networks While Learning on a Sequence of Tasks

Continual learning is the problem of learning on a sequence of tasks and the core issue in this domain is that of balancing catastrophic forgetting of prior knowledge with generalization over new tasks, known as the stability-plasticity dilemma. This work introduces CL's effective model capacity (CLEMC) to theoretically formalize how this balance depends on the neural network (NN), the tasks, and the optimization procedure. In this talk, we demonstrate that CLEMC, and thus the balance point, is non-stationary and the interplay between tasks, neural network and the optimization procedure is an evolving dynamical system. In particular, we discuss the use of optimal control techniques to model this dynamical system and study the evolution of CLEMC. We hypothesize that regardless of the NN architecture and optimization method, the network's ability to represent new tasks diminishes if the new tasks' data distributions differ significantly from previous ones. We cement this hypothesis using various NNs, from small feed-forward and convolutional networks to transformer-based language models with millions of parameters (8M and 134M), validate these theoretical findings.

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MS175

Delayed Bifurcations can Generate an Emergent and Universal Robustness to Spatio-temporal Variation in Pattern Formation

Biological systems use spatio-temporally varying input signals to self-organise into macroscale structures (patterns) that are vital for many physiological processes. As observed by Turing in the 1950s, these patterns are in a state of continual development, and are usually transitioning from one pattern into another. How can this self-organising process be robust in the presence of confounding effects caused by unpredictable or heterogeneous environments? Through multiscale analysis, I present a general theory of pattern formation in the presence of spatio-temporal input variations, and show how biological systems can generate non-standard dynamic robustness for 'free' over physiologically relevant timescales. I apply this theory to paradigmatic pattern-forming systems, and predict that they are robust with respect to non-physiological variations in input signal. More broadly, I show how the dynamics of pattern-forming systems with spatio-temporally varying parameters can be classified based on the bifurcations in their governing equations. References [1] MP Dalwadi and P Pearce (2021), Emergent robustness of bacterial quorum sensing in fluid flow, Proceedings of the National Academy of Science USA, 118(10):e2022312118 [2] MP Dalwadi and P Pearce (2023), Universal dynamics of biological pattern formation in spatio-temporal morphogen variations, Proceedings of the Royal Society A, 479: 20220829

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MS175

The Influence of Autotoxicity on Travelling Vegetation Spots in Sloped Semi-Arid Environments

Vegetation patterns are important hallmarks for the resilience of the underlying ecosystem. In semi-arid environments, the interaction between vegetation and water governs the emergence of stationary and moving patterns. We study the influence of the ecological factor known as autotoxicity on the existence and dynamics of vegetation patterns, by extending known vegetation-water reaction-advection-diffusion models with an autotoxicity interaction ODE. We show how autotoxicity introduces a new spatial scale, and can be used to explain and predict multi-scale structures within patterns. Moreover, we highlight the influence of autotoxicity on the propagation speed of patterns, in comparison with the slope of the terrain. Our analysis uses geometric singular perturbation theory, which we complement by numerical continuation of the constructed pattern solutions and direct numerical simulation of the full PDE-ODE model.

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MS175

Localised, Extended and Dynamic Patterns on a Finite Disk

A non-variational complex generalisation of the cubic-quintic Swift-Hohenberg model (CSH35), is studied in two different spatial domains: a large one-dimensional spatial domain with periodic boundary conditions, and a small-radius finite disk with Neumann boundary conditions. Using a combination of numerical (direct numerical simulations and numerical continuations using pde2path) and analytical (weakly non-linear analysis) techiniques, branches of traveling and standing waves are found in both domains. Secondary birurcations of these waves solutions connect to branches of localised version of them. Notably, the family of localised standing waves seem to exhibit a generalisation of the so-called Snaking scenario. In the case of the finite disk, branches of waves are found for solutions with qualitatively different spatial solutions such as wall-modes or spirals.

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MS175

Exponential Asymptotics for the Study of 'Localized Spatiotemporal Patterns' on the Line

Exponential asymptotics is a well-known technique that has been used sometimes to study the region in the parameter space where localized spatial patterns appear close to a codimension-two Turing bifurcation point in which the criticality of this bifurcation changes. My talk will start with the use of this technique to study the width of the snake for a general reaction-diffusion system, showing multi-component examples where it has been applied. Then, I will talk about a general calculation and code that can do those calculations automatically to obtain the criticality of Turing-wave bifurcations and draw bifurcation curves in order to show an example where codimension-two points for Travelling and Standing waves occur. This serves as a motivation for what I am working on now, which is the extension of the use of exponential asymptotics to study what happens at exponentially small scales near codimension-two Turing-wave bifurcation points.

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MS176

Higher-order Connectomics of Human Brain Function in Health and Disease

Traditional models of human brain activity often represent it as a network of pairwise interactions between brain regions. Going beyond this limitation, recent approaches have been proposed to infer higher-order interactions from temporal brain signals involving three or more regions. However, to this day it remains unclear whether methods based on inferred higher-order interactions outperform traditional pairwise ones for the analysis of fMRI data. In this talk I will introduce a novel approach to the study of interacting dynamics in brain connectomics, based on higher-order interaction models. Our method builds on recent advances in simplicial complexes and topological data analysis, with the overarching goal of exploring macro-scale and time-dependent higher-order processes in human brain networks. I will present our preliminary findings along these lines when studying the healthy and the diseased brain network; finally, I will discuss limitations and potential future directions for the exciting field of higher-order brain connectomics

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MS176

Using Stochastic Process Models to Understand Rhythmic and Aperiodic Neural Dynamics in Health and Disease

Clinical practice in neurological disorders often relies on biomarkers in neural electrophysiological recordings whose underlying mechanisms are unknown. Studying the mechanisms of these biomarkers is essential for improving treatments and advancing the understanding of brain function in health and disease. Historical research uncovered countless rhythmic biomarkers, from beta oscillations in Parkinsons disease to slow waves in disorders of consciousness. Patterns of rhythmic coupling across brain regions also change with brain state, such as the transition from occipitally- to frontally-coherent alpha rhythms in propofol anesthesia. More recently, there has been an increase in studies reporting broadband aperiodic biomarkers such as the power law exponent of the power spectrum, which changes systematically with age, epilepsy, ADHD, and more. Here, I will present two statistical frameworks for linking empirical rhythmic and broadband biomarkers to theoretical dynamical systems models of their mechanisms. The first framework uses switching state space models of oscillatory networks to capture dynamic patterns of functional connectivity. The second framework uses filtered, doubly stochastic point processes to capture the broadband consequences of dynamic ensemble activity. These models can be used to detect changes in biophysically interpretable parameters, leading to mechanistic insights about clinically relevant brain states.

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MS176

Virtual Brain Twins: from Basic Neuroscience to Clinical Use

Virtual brain twins are personalized, generative and adaptive brain models based on data from an individuals brain for scientific and clinical use. In this talk, we will describe the key elements of virtual brain twins and present the standard model for personalized whole-brain network models. We will detail the most advanced application in epilepsy, including the diagnosis of epileptogenic networks, virtual surgery and stimulations. Then we will extend the application of virtual brain twins to healthy ageing and five clinical diseases: epilepsy, Alzheimers disease, multiple sclerosis, Parkinsons disease and psychiatric disorders.

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MS178

Bifurcation Enhances Odor Timing Encoding for Olfactory Navigation

MOTIVATION: Most animals locate food and mates through olfactory navigation, extracting temporal, positional, and directional information about odor sources from downwind signals. Turbulent air disrupts continuous odor streams into discrete filaments, resulting in intermittent signals and intensity fluctuations. Olfactory receptor neurons (ORNs) are the first to process this information by detecting odorant molecules and generating action potentials sent to the brain. In Drosophila, ORNs adapt their gain based on the mean and variance of odor signals, maintaining proximity to their firing threshold. However, the mechanism of variance adaptation and its role in encoding odor fluctuations remain unknown. RESULTS: We developed a conductance-based model of Drosophila ORNs to examine their odor encoding properties. We find that when operating near a bifurcation point in their firing dynamics, ORNs are naturally invariant to signal variance and exhibit enhanced capacity for encoding the timing, duration, and intensity of odor fluctuations. Additionally, adaptation to the mean signal intensity maintains ORNs near this bifurcation. Thus, by exploiting a bifurcation in the firing dynamics of ORNs, crucial navigational cues are effectively captured at the first processing stage of the Drosophila olfactory system. These results suggest that neurons in various sensory systems may also utilize proximity to bifurcations to optimize encoding capabilities.

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MS178

From Metaphor to Model: Generalized Landscapes for Cell Fate Decision

Cellular differentiation is often illustrated using the Waddington landscape metaphor, but recent theoretical and experimental advancements have sought to make this metaphor more quantitative. In this talk, I will present a mathematical framework for constructing these landscapes from both qualitative and quantitative data. I will first demonstrate how explicit models for vertebrate segmentation, based on the segmentation clock, can be developed, which naturally leads to testable bifurcation diagrams. Additionally, I will show how combining this framework with machine learning enables the generation of hundreds of candidate landscapes that fit differentiation data. Finally, I will discuss how the statistical properties of these solutions suggest that the topography of differentiation landscapes can be predicted with high accuracy.

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MS178

A Feedback Motif for Critical Behavior and Robust Signal Amplification

Many biological systems are very sensitive to small input signals. A tempting hypothesis is that these systems operate close to bifurcation or critical points, where the system's response exhibits a diverging susceptibility to the control parameter and small signals are amplified into a large collective response. However, a common concern is that being close to these points requires fine-tuning of parameters, which seems impossible for noisy biological systems subject to varying environments. Based on several examples ranging from snake thermosensing and E. coli chemosensing to fly olfaction, we have investigated a feedback motif inspired by self-organized criticality that robustly maintains these systems close to their respective critical point. The key ingredient is that the collective response feeds back onto the control parameter. Such a feedback scheme works well if just a single control parameter needs tuning. But robust critical behavior has also been found in high-dimensional systems like plasma membranes made up from thousands of components and in mammalian hearing where local activity of hair cells brings the whole cochlea to the edge of instability. Here we argue how these systems could find the critical manifold in the high-dimensional parameter space and why critical behavior might occur naturally in high-dimensional systems.

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MS178

Ghost Channels and Cycles Guiding Long Transients in Natural Systems

A fundamental characteristic of living systems is sensing and subsequent robust response to continuously varying environmental signals. Even seemingly simple systems, such as single cells or single-cell organisms, reveal higher-order computational capabilities that go beyond simple stimulus-response association. Developing a theoretical framework to characterize transient sets in dynamical systems, we describe how ghost sets can be utilized as a memory to integrate information from time-varying signals. We have identified experimentally that these states are an emergent feature of cell-surface receptor networks organized at criticality, which they exploit for memory-based navigation in changing environments. Furthermore, by formulating a theory of computation with ghost sets, we explore theoretically and experimentally basic paradigms of computation of time on the level of single cells, but also neuronal networks.

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MS179

Using an Open-loop Architecture to Parameterise Models of the HPA-axis Response to Heart Surgery

The ability of the hypothalamic-pituitary-adrenal (HPA) axis to respond dynamically to stressors is critical for healthy function. Surgical interventions such as heart surgery constitute an extreme but predictable exogenous stressor. Post-surgical recovery critically depends on a robust, dynamic response from the HPA axis to prevent uncontrolled inflammation. Failure to control the inflammatory response may lead to prolonged hospitalisation and even death. Therefore, the ability to predict the post-surgical stress response before surgery could have a major impact on individualised treatment. We developed dynamical systems models of HPA-axis hormones (e.g., cortisol) written in terms of delay differential equations (DDEs). These models exhibit limit cycle solutions via delayed negative feedback and explain the ultradian rhythmicity of HPA-axis hormones. Exogenous stressors are modelled as large, transient perturbations of these typical hormonal rhythms. We parameterised these models to individual patients undergoing heart surgery and identified potential targets of signalling molecules needed to mount a stress response. By leveraging an open-loop architecture, i.e., replacing model variables with data in a non-autonomous subsystem, we were able to improve the tractability and calibration of the model by limiting the number of free parameters and accounting for unobserved inputs to the system.

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MS179

Incorporating Physiological Constraints in Estimates of Insulin Secretion Rate

Features of insulin secretion rate (ISR) during an oral glucose tolerance test (OGTT) provide insight into an individuals metabolic health, and specifically, beta-cell function. However, during an OGTT, we cannot measure ISR directly. We propose a Bayesian hierarchical model (BHM) that incorporates physiological constraints to precisely infer continuous ISR profiles from discrete C-peptide data. We take C-peptide as the output of a common C-peptide dynamics model with ISR as a forcing function, and the logarithm of ISR as a Gaussian process with a quadratic mean trend. The quadratic component captures the overall rise and fall generally observed in ISR during an OGTT, and the exponential form of ISR precludes non-positive values across the distribution of ISR profiles. Positivity propagates through to the posterior distribution obtained in inversion. Further, the method furnishes a linear approximation of the non-linear transformation from log-ISR to C-peptide that adheres to the constraints. Results obtained from the log-transformed model correlate well with the purely Gaussian model, however, the log-transformed model yields more precise estimates, characterized by narrower credible envelopes. In this presentation, we develop the BHM, outline the inversion and uncertainty quantification methods, and compare the ISR results obtained from the log-transformed and purely Gaussian models on a set of OGTT data from youth participants with and without cystic fibrosis.

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MS179

Dynamic Physiologic Model of Simultaneous Cortisol and Cortisone Dispositions Including Interconversions in Humans

INTRODUCTION: We developed a prediction model for time-varying plasma concentrations of free cortisol (F) and cortisone (E) by integrating relevant 11-beta-hydroxysteroid dehydrogenase (11-HSD) enzyme activities into a system of ODEs previously validated for in vivo cortisol disposition in healthy humans (Dorin et al, 2022). METHODS: Interconversions by 11-HSD1 (E to F, hepatic) and 11-HSD2 (F to E, renal) are represented by conservation of mass in a flow (mass/time) model. Competitive F and E binding to CBG used mass action equations, Coolens simplification was used for E/F binding to free albumin (Dorin Qualls 2024). RESULTS: Steady state properties of the model and monoexponential vs. saturable enzyme kinetics were explored in test bed analysis, as were parameter simplifications related to similarities of E and F for albumin-binding, diffusion (Ficks law), and elimination. The EF model explains the transitory appearance of E after cortisol bolus (Perogamvros et al, 2011) and extra-adrenal cortisol production observed in stable isotope experiments. CONCLUSIONS: Correspondence between model-predicted and measured F and E provide preliminary validation of the proposed generalization of the 4-compartment cortisol model. This approach to modeling enzyme activities in vivo may be useful in assessment of 11-HSD mediated F and E appearance rates and advantageous relative to other methods (e.g. stable isotope dilution or oral cortisone challenge test).

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MS180

Coupled Ocean-Atmosphere Data Assimilation Using Sliding Window POD

Predicting the state evolution of coupled ocean-atmosphere systems remains challenging due to the nonlinear sensitivity of these systems to initial condition inaccuracies and model parameters. Data Assimilation (DA) techniques enhance state estimates by combining model simulations with real-time observational data. Coupled systems, however, are characterized by nonlinear evolution, non-Gaussian uncertainties, and high dimensionality. To address these complexities, we apply a dynamically adaptive projection approach using Sliding Window Proper Orthogonal Decomposition (SW-POD) within the Modular Arbitrary-Order Ocean-Atmosphere Model (MAOOAM). The SW-POD enables DA to respond flexibly to time-dependent interactions across oceanic and atmospheric subsystems by recalculating projections based on recent system evolution. This adaptive framework improves the accuracy of coupling analyses, enhances forecast skills, and improves computational efficiency.

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MS180

Long-Time Accuracy of Ensemble Kalman Filters for Chaotic Dynamical Systems and Surrogate Models

Filtering is concerned with online estimation of the state of a dynamical system from partial and noisy observations. In applications where the state is high dimensional, ensemble Kalman filters are often the method of choice. This talk will study the long-time accuracy of ensemble Kalman filters. We introduce conditions on the dynamics and the observations under which the estimation error remains small in the long-time horizon. Our theory covers a wide class of dissipative chaotic dynamical systems, which includes the Navier-Stokes equations and Lorenz models. In addition, we prove long-time accuracy of ensemble Kalman filters with surrogate dynamics, thus validating the use of machine-learned forecast models in ensemble data assimilation.

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MS180

Decomposition of Likelihoods and Projection Techniques for Multi-Scale Data Assimilation

Data assimilation (DA) combines physical models and observational data to improve predictive capabilities and quantify uncertainties in future states of the physical model. Challenges for DA include highly nonlinear behavior in models and data, high dimensionality, and quantifying non-Gaussian uncertainties. In this talk we focus on projection-based decomposition of both the physical model solutions and observational data to reduce effective dimensionality. We highlight recent progress in the application of Particle Filters (PFs) to model non-Gaussian uncertainties employing reduced dimensional surrogate physical and data models. The first technique is based upon the use of POD type projections obtained from short forecasts and the second is based on the decomposition of Gaussian likelihoods using a block matrix generalized inverse result to obtain a combined PF/ensemble Kalman filter. Numerical results illustrate the effectiveness of the techniques.

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MS181

Sparse DEIM: State Estimation from Sparse Observational Data Using Recurrent Neural Networks

Discrete empirical interpolation method (DEIM) estimates a function from its incomplete pointwise measurements. Unfortunately, DEIM suffers large interpolation errors when few measurements are available. Here, we introduce Sparse DEIM (S-DEIM) for accurately estimating a function even when very few measurements are available. To this end, S-DEIM leverages a kernel vector which has been neglected in previous DEIM-based methods. When the function is generated by a continuous-time dynamical system, we propose two data assimilation methods which approximate the optimal kernel vector using sparse observational time series. The first method uses the governing equations, whereas the second method uses recurrent neural networks to learn the unknown kernel vector. We prove that, under certain conditions, data assimilated S-DEIM converges exponentially fast towards the true state.

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MS181

Autonomous Control of Multi-Scale Bio-Inspired Robots in the Averaged Nonlinear Dynamics

The highly agile and extreme behaviors of many biological systems offer examples for future research directions to target similar mobility in bio-inspired robots, understanding of the complex dynamics, and subsequent design of a robust and adaptive control framework. Examples of extreme behaviors in biological systems are the fast oscillation-driven maneuvers of bees flapping their wings around 200 Hz and the rapid impulsive striking of mantis shrimp, releasing their stored potential energy within milliseconds. The challenges for control of robots with similar extreme behaviors lie in the highly nonlinear dynamics operating over multiple timescales. Specifically, one has to account for fast dynamics (extreme motions) and slow dynamics (time-averaged motion or slower drift in the system), and the time-varying actuation model in the high-frequency regime (fast-dynamics) vs the low-frequency regime (slow dynamics). This talk will address the control-theoretic aspects of dealing with such challenges in bio-inspired robots based on the first principles of mathematical system theory. Recent progress in controlling the Harvard Robobee, an insect-scale flapping-wing vehicle that flaps its wings around 150 Hz, and a bird-scale robot flapping around 20 Hz.

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MS181

Data Assimilation in Reduced-Order Models of Earthquake Sequences

We introduce a dynamical model that captures the physics of fault friction to simulate earthquake cycles, opening new possibilities for time-dependent earthquake hazard assessment. This model exhibits chaotic, multiscale behavior across both time and space, including extreme events, which reflects the inherent complexity of earthquake dynamics. The limited availability of observational data across some of the spatiotemporal scales poses significant challenges for solving inverse problems and performing data assimilation. Developing a reduced-order model (ROM) that retains the system's key dynamics while reducing computational demands is therefore highly beneficial. However, the models complexity makes it challenging to construct an effective ROM in parameter regimes where small-scale processes, such as earthquake nucleation, become increasingly fine and difficult to capture. Here, we present a ROM tailored to selected parameter regimes and apply data assimilation under a realistic observation operator, highlighting the limitations of our approach. Preliminary results indicate that while the ROM effectively captures the essential dynamics in certain cases, further refinements are needed to address multiscale behavior across broader parameter settings.

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MS182

A Nonlinear Wavemaker and a Nonlinear Radiation Condition

A wavemaker is a ubiquitous laboratory device for the generation of waves from the boundary of a wave medium, e.g., a piston at the end of a water wave flume. A mathematical model of this is the quarter-plane initial-boundary value problem consisting of constant data at $t = 0$ representing a quiescent initial state subject to an asymptotically ($t \to \infty$) time-periodic boundary condition at $x = 0$. Recent work on the wavemaker problem for a class of linear, third-order dispersive evolutionary equations proved i) the solution is asymptotically time-periodic for each fixed $x > 0$ and ii) the radiation condition: for a given input frequency, the unique wavenumber k is selected by either positive group velocity for real k (propagating waves) or spatial decay as $x \to \infty$ for imaginary k (evanescent waves) according to the linear dispersion relation. In this talk, the nonlinear wavemaker problem is considered for the Korteweg-de Vries equation with a boundary condition corresponding to a cnoidal traveling wave solution evaluated at $x = 0$. Using Whitham (nonlinear wave) modulation theory, corroborated by numerical solutions, it is demonstrated that asymptotically, either of the following is generated: 1) a time-periodic, propagating cnoidal wave solution with the same frequency but possibly different amplitude and mean as the boundary data, or 2) a dynamic, algebraically decaying wave train that is not time-periodic.

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MS182

Slow Optical Pulses in Two Level Active Media

Regimes of slow light-pulse propagation through two-level, active optical media are studied as a function of the optical-medium relaxation rates, in particular the relaxation of the medium polarization, using the classical, two-level Maxwell-Bloch model. For pulses injected as soliton-shaped and for slow relaxation rates, we expectedly find damped-soliton propagation, during which the pulse amplitude and velocity are adiabatically locked, proportionally to one-another and to the inverse pulse width. In the course of its propagation, the pulse decays, broadens, and slows down until it stops and is extinguished altogether. For faster relaxation rates, the injected pulse splits in two, a damped soliton, and a small precursor pulse comprising radiation ripples, which decays and accelerates towards the speed of light in vacuum. For very fast polarization relaxation, only the precursor remains, and is consolidated in a single pulse. Our simulations predict that the light pulse in such a slab does not slow down, but rather starts propagating very slowly and then accelerates.

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MS183

Efficient Computation of Periodic Orbits of Forced Impact Oscillators with Delays

In engineering practice, vibration mitigation frequently employs acceleration-based feedback loops due to their simplicity and cost-effectiveness. Another approach is to employ impact dampers that effectively dissipate vibrations. The impacts induce periodic oscillations characterized by discontinuous velocity changes. Combining the two methods results in systems that are described by non-smooth neutral delayed differential equations. The analysis of their stability and steady-state motion is challenging as the velocity discontinuities caused by impacts propagate through delayed feedback loops, replicating infinitely many times. For example, suppose the ratio between the excitation period and time delay is irrational. In that case, the velocity function might accumulate infinitely dense discontinuities over time, indicating that periodic solutions might not even exist. In this talk, we present a general and performant iterative method for finding periodic orbits in such systems. We determine the stability based on the Floquet multipliers by constructing the corresponding Krylov subspace using a direct simulation-based matrix-free approach. We show that it is efficient and robust in handling discontinuities through the analysis of a harmonically forced oscillator with delayed acceleration feedback with elastic and hard impacts.

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MS183

Noise Induced Performance Enhancement in TET Through Vibro-Impact System

Excessive vibration in engineering systems can cause human discomfort and even lead to catastrophic failures. One of the promising techniques for vibration mitigation is Targeted energy transfer (TET), where energy is irreversible transferred from a primary oscillator (LO) to an auxiliary system. Recent studies on TET through vibro-impact (VI) based nonlinear energy sink (NES) have demonstrated enhanced performance over a broad spectrum. In VI-NES, where a ball oscillates inside the LO, energy transfers through the impacts and mitigates the vibration of the LO. Prior studies on VINES examined limited parameter ranges with the smaller mass ratio and external excitation near the resonant frequency. In this study, we are considering fully non-smooth system, applying novel analytical and numerical analyses of externally excited VI-NES over a broad range of parameters for different periodic dynamics. Additionally, we consider the effects of random fluctuations, called noise, in the external excitation, which have the potential to affect the energy transfer mechanism. While previous probabilistic studies are restricted to the conventional TET mechanisms our preliminary results indicate an enhanced performance of VI-NES for certain types of noise. This study investigates the stochastic bifurcation structure of the TET, integrating non-smooth analysis with a probabilistic framework and provides insights into key performance metrics for VI-NES system.

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MS184

Computing Orbits And Asymptotic Sets Around Collinear Lagrange Points Using Isolating Neighborhoods

Isolating blocks and isolating neighborhoods have previously been used to examine the behavior of trajectories around the collinear Lagrange points in the circular restricted three-body problem (CRTBP). More recently, we have implemented computational methods to directly compute the motion of various types of trajectories around the Lagrange points. Specifically, bisection methods have been used in combination with a left-right exit scheme to directly compute transit trajectories and corresponding portals in space where transit trajectories are required to travel through. An extension of these methods allows the direct computation of both forward and backward asymptotic trajectories, or invariant manifolds, approaching the isolated invariant set around the Lagrange point, and it has been confirmed using these methods that the isolated invariant set has the characteristics of an invariant three-sphere. By computing the intersection of forward and backward asymptotic sets within the invariant three-sphere, initial states on specific periodic and quasi-periodic orbits within the invariant three-sphere are also directly computed. An orbit tracking algorithm is then implemented to compute these orbits for long time periods with only minor corrections. The resulting periodic and quasi-periodic orbits are explored along with their corresponding asymptotic sets. Possible applications of these methods for computing orbits to nonautonomous systems are also described.

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MS184

Visualizing The Topology Of Transport In The Restricted 3-Body Problem

Transport in the Restricted 3-Body Problem (R3BP) is accomplished through the invariant manifolds of the unstable orbits. In recent work, we have visualized the tubular structure of the toroidal manifolds of quasiperiodic orbits. This prior work extends a discrete one-form-based 3D toroidal surface meshing method to high-dimensional toroidal point clouds sampled in the state space of quasi-periodic orbital trajectories in the R3BP. The resulting meshes are enhanced through the application of an embedding-agnostic triangle-sidedness assignment algorithm. This significantly increases the intuitiveness of interpreting the meshes after downprojecting to 3D for visualization and provides a framework for distinguishing the interior and exterior of the manifold. Using this same technique, we can visualize the tubular structure of periodic orbits. The problem is more complex for visualizing the invariant manifolds of the 2D quasiperiodic orbits, which are 3D structures within the 5D energy surface of the R3BP. The problem is further complicated by the fact that some of the quasiperiodic orbits of the R3BP have self-intersections within the configuration space. Understanding these manifolds on both a topological and visual level is of critical importance to the space mission design process because they guide the transport of objects in space, including asteroids, comets, dust particles, and spacecraft. In this presentation, we describe our research of this problem to date.

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MS184

Secondary Resonance Overlap Inside Unstable Resonant Spacecraft Orbit Families in Outer Planet Moon Systems

The phenomenon of mean-motion resonance overlapping, generated by heteroclinics between unstable resonant orbits, is crucial for the generation of global phase space transport in celestial systems. This is useful for low-energy space mission trajectory design. However, leveraging this effect first requires computing unstable resonant orbits, which requires an understanding of their topological structure. While these are simple periodic orbits in the planar CRTBP, when the periodic forcing from another large body is also taken into account (e.g. in multi-moon systems), the usual expectation of periodic orbits to persist as dynamically equivalent 2D tori does not in fact always hold true. This presentation will focus on how various types of unstable resonant orbits are created when influenced not only by the gravity of their resonant moon, but a perturbing one as well. The perturber acts on families of unstable resonant orbits through secondary resonances, shown to be an important effect on the dynamics inside the cylinder formed by the orbit family. In regions where the perturbation is strong, these secondary resonances overlap inside the cylinder, destroying the torus equivalents of PCRTBP orbits completely and replacing them with topologically different ones. We demonstrate this phenomenon for a number of the outer planets, their moons, and resonances, showing this to be a general phenomenon to be taken into account when using resonant orbits for outer planet mission design.

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MS184

New Method for Computing Invariant Manifolds and Applications

Poincar stated that periodic orbits are the only openings through which we can penetrate nonlinear dynamics. For the problem of transport in phase space, invariant manifolds of unstable periodic orbits provide the answer. For Hamiltonian systems, the unstable orbits have asymptotic trajectories that depart the unstable orbits and asymptotic trajectories that approach the unstable orbits; they are respectively called the unstable and stable manifolds of the unstable orbits. Invariant manifolds are typically computed from the eigenvectors of the monodromy matrix. We discovered a very simple method for computing the invariant manifolds. Let P be a point on the unstable orbit, let V be an arbitrary unit tangent vector at P, and $e \ll 1$. Then integrating $(P + e * V)dt$ forward in time $[0, t]$, we get $\mathrm{WU}(P)$ is an approximation of the unstable manifold at P. Integrating $(P + e * V)dt$ backwards in time, $[-t, 0]$, we get $\mathrm{WS}(P)$ is an approximation of the stable manifold starting at P. For many applications, these approximations are more than adequate. The reason this works is the eigenvectors of the monodromy matrix is a complete set of basis vectors of the tangent space at P. V can be expanded as a linear sum of these basis vectors. When the integrals are executed, the unstable direction will increase exponentially and overwhelm the rest of the basis components of V. Similarly for the stable manifold when integrating backwards. This method works for any unstable object in phase space.

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MS185

Population Dynamics of Spiking Neural Networks with Delayed Coupling

We investigate the collective dynamics of a network of Izhikevich neurons with global delay coupling using a mean-field approximation, valid in the thermodynamic limit. Our study emphasizes the impact of heterogeneous currents, adaptation intensity, and synaptic delay on the emergence of collective oscillations. The effects of the first two factors vary across different scenarios but mainly result from the balance of excitatory drives, including input currents that cause neurons to spike, adaptation currents that terminate spiking, and synaptic currents that predominantly favor spiking in excitatory networks but hinder it in inhibitory cases. Our perturbation and bifurcation analysis uncover interesting behavioural transitions in both limits of extremely weak heterogeneity and coupling strength. Furthermore, we find that synaptic delays have little influence on generating collective oscillations in weakly coupled heterogeneous networks, though this impact becomes more pronounced with increased heterogeneity. A larger delay does not necessarily enhance oscillation likelihood, especially in weakly adapting networks. Beyond that, delays serve as excitatory drives, promoting oscillations and sometimes inducing new macroscopic dynamics. Specifically, Torus bifurcations may occur in a single population of neurons without an external drive, playing a key role in the emergence of cross-frequency coupling.

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MS185

Dynamics of Coupled Neural Populations: The Role of Synaptic Dynamics

The study of neural populations is of increasing interest. In the literature, there are two recent mean-field models that represent the dynamics of heterogeneous all-to-all coupled QIF spiking neural networks. One of these models takes the synaptic dynamics into account, and the other does not. Both models are linked through a parameter related to the synapsis. In this presentation, the dynamical changes observed when this parameter is varied are studied using techniques such as numerical continuation and the spike-counting sweeping. This is joint work with Roberto Barrio, Jorge A. Jover-Galtier, Carmen Mayora-Cebollero, Luca Prez and Sergio Serrano

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MS185

Neurologically Motivated Coupling Functions in Models of Motor Coordination

We present an analysis of two Haken–Kelso–Bunz (HKB) oscillators coupled by a neurologically motivated function. We study the effect of time delay and weighted self-feedback and mutual feedback on the synchronization behavior of the model. We focus on identifying parameter regimes supporting experimentally observed decrease in oscillation amplitude and loss of anti-phase stability that has inspired the development of the HKB model. We show that a combination of cross-talk and nonlinearity in the coupling, along with physiologically relevant time delay, is able to quantitatively account for both drop in oscillation amplitude and loss of anti-phase stability in a frequency dependent manner. Furthermore, we demonstrate that the transition between discrete and rhythmic movements could be captured by this model. To this end, we carry out theoretical and numerical analysis of the emergence of in-phase and anti-phase oscillations.

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MS185

Multiplicative Shot-Noise: A New Route to Stability of Plastic Networks

Fluctuations of synaptic weights, among many other physical, biological, and ecological quantities, are driven by coincident events of two parent processes. We propose a multiplicative shot-noise model that can capture the behaviors of a broad range of such natural phenomena, and analytically derive an approximation that accurately predicts its statistics. We apply our results to study the effects of a multiplicative synaptic plasticity rule that was recently extracted from measurements in physiological conditions. Using mean-field theory analysis and network simulations, we investigate how this rule shapes the connectivity and dynamics of recurrent spiking neural networks. The multiplicative plasticity rule is shown to support efficient learning of input stimuli, and it gives a stable, unimodal synaptic-weight distribution with a large fraction of strong synapses. The strong synapses remain stable over long times but do not run away. Our results suggest that the multiplicative shot-noise offers a new route to understand the tradeoff between flexibility and stability in neural circuits and other dynamic networks.

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MS186

Asymptotic Analysis of Hill's Orbits in the (2+2)-Body Problem

We apply the the Poincare-Lindstedt method to obtain asymptotic approximations of the Hill's orbits in the (2+2)-body problem. This requires finding a fundamental matrix solution for a non-autonomous linear system of four first-order ODEs. We accomplish this by first guessing three linearly independent solutions, and then by using Liouville's Theorem and Variation of Parameters to compute the fourth linearly independent solution.

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MS186

Hyperbolic Sets in Three Body Problem

We present a general result from Lagrangian dynamics on hyperbolic invariant sets. This result is used to obtain information on hyperbolic sets in the three body problem. The abstract should be no longer than 1500 characters, including spaces. Only input the abstract text. Don't include title or author information here.

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MS186

Convex Four-Body Central Configurations

Central configurations play a key role in understanding solutions of the Newtonian n-body problem. From rest, a central configuration (c.c.) will collapse in on itself homothetically, while given the correct initial velocity, a planar c.c. will rotate rigidly about its center of mass (a relative equilibrium). We focus on four-body central configurations whose shape is *convex*, that is, the bodies from a convex quadrilateral with no body contained in the convex hull of the other three. One of the outstanding conjectures in the field is that for a given ordering of the bodies and a fixed choice of masses, there is a *unique* four-body convex central configuration. Uniqueness has been proven for certain classes of configurations, such as kites, trapezoids, and co-circular configurations. Based on some recent work on convex kite c.c.'s, we approach the problem using tools from differential topology (e.g., the Poincaré-Hopf Index Theorem) and computational algebraic geometry (e.g., Grobner bases). This is preliminary work.

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MS186

Scaling Symmetries, Relative Equilibria, and Central Configurations in Hamiltonian Systems and the n-Body Problem

In this talk, well discuss how scaling symmetries provide fresh insights into n-body problems and Hamiltonian systems, with a focus on relative equilibria and central configurations. By extending symplectic methods to include scaling symmetries, we introduce a conformal momentum map that captures the effects of scaling within Hamiltonian dynamics. This leads to the definition of an augmented Hamiltonian and an augmented potential, which allow us to derive the equation for relative equilibria specific to scaling symmetries and to generalize the equations governing central configurations in Hamiltonian systems that admit scaling symmetries. When applied to the Newtonian n-body problem, these methods recover the classical equations for central configurations. This approach offers a new perspective on Hamiltonian dynamics and deepens our understanding of systems with intrinsic scaling behaviors.

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MS187

Braiding Dynamics of Topological Defects in Confined Active Nematics

Active nematics exhibit topological chaos in the bulk driven by the motions of topological defects. Strong confinement can lead instead to ordered flows together with periodic motions of defects. Recently, a periodic motion of three $+1/2$ disclinations known as the golden braid was demonstrated in the interior of a cardioid, with the cardioids cusp effectively pinning a -1/2 topological charge. Can this principle be generalized to produce ordered flows with even greater numbers of $+1/2$ defects by encoding their excess charge into the boundary conditions? We investigate this question with simulated active Beris-Edwards nematodynamics together with tools from braid theory. We show that when excess topological charge is programmed into the anchoring conditions or boundary geometry, we recover the golden braid motion of three defects and we predict a silver braid motion of four defects. We rationalize these findings by demonstrating how to predict time-averaged vortex structure from the boundary charge. Based on a simple counting argument for vortices and defects, our theory predicts that no such ordered flow will emerge for five or more $+1/2$ defects; our simulations corroborate this prediction by exhibiting only aperiodic defect swaps. Finally, we discuss implications of our findings for the production of topological entropy by active nematics.

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MS187

Geometrical Control of Active Fluid dDynamics

In recent years, a new direction in non-linear dynamics has emerged: chaotic transport in active fluids. This field brings together concepts from soft matter such as liquid crystal physics with analysis techniques from fluid dynamics. In active nematic systems, fluid flows are dominated by active self-propulsion of the fluid components and emergent motile topological defects, resulting in self-mixing phenomena. In this talk I will review recent experimental work from our lab based on a biologically-inspired active nematic system constructed from microtubules and kinesin molecular motors. I will present the effects of geometrical confinement on this system, quantifying the effects of confinement in wells of varying topological charge on flow dynamics.

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MS187

Chaotic Advection in Active Matter

Recent years have seen a surge of interest in active materials, in which energy injected at the microscale gives rise to mesoscale coherent motion. Such active systems exhibit similarities to living matter in that they are not described by standard equilibrium thermodynamics. We begin with a general introduction to active materials and this minisymposium in particular. We then move on to discuss one prominent example of an active material: an active 2D "liquid crystal" composed of microtubules aligned in a nematic phase. The activity is generated by molecular motors that consume ATP to produce local shearing between the microtubules. The resulting 2D fluid flow exhibits self-generated mesoscale chaotic dynamics with a characteristic folding and stretching pattern. We analyze this dynamics from the perspective of chaotic advection, employing tools from nonlinear dynamics. We show that the fluid can be viewed as "stirred" by topological defects. Typically, these defects move in an irregular, chaotic pattern. However, we explore conditions under which the topological defects can be coaxed to perform regular periodic motion, thus bringing some degree of order to the chaos.

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MS187

Realizing Optimal Dilation Pseudo-Anosov Maps with Confined Active Nematic Flows

When trying to understand the chaotic dynamics of a surface flow, a natural tactic is to simplify (for more powerful tools) and hope that the core dynamics are retained. For example: replace the flow with a flow map and gain access the Nielsen-Thurston classification of mapping class groups. Replace this map with the simplest possible map in its mapping class - the pseudo Anosov (pA) representative - and get a measured foliation and the map dilation (a measure of the map's complexity). Finally, of all the possible pA maps, consider only those that have optimal dilation (as large as possible given some constraints). While it seems unlikely that after all these simplifications, the final model faithfully retains the full dynamics of the initial surface flow, there are experimental flows where this appears to be the case: confined active nematic microtubule (ANMT) flows. Active Nemaics are a now-canonical active matter system, and we believe that their strong connection to surface map theory needs to be better appreciated. The measured (unstable) foliation corresponds to the ANMT director field, the singularities in the pA map correspond to the +1/2 and -1/2 defects, the map dilation can be affected by the activity (e.g. ATP), and when confined geometrically, the ANMT will realize pA maps with optimal dilations. In this talk we will consider ANMT flows confined to annuli, spheres, ellipsoids, tori, disks, and hyperbolic surfaces.

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MS188

Coupled Dynamics on Hypergraph: Beyond Pairwise Interactions

Since long-modelling real-world complex systems are made up of a large number of interacting dynamical units, they incorporate only pairwise interactions. Increasingly, it has been realized that a variety of complex systems, such as the Brain, society, weather, etc., not only have their units forming higher-order interactions, but also such interactions might govern the associated coupled dynamics, yielding completely different behaviours than those predicted by pairwise interactions. Using phase-lagged coupled Kuramoto oscillators with higher-order couplings as a case study, we will demonstrate such a behaviour, that is, first-order transition to cluster synchronization along with associated numerical and analytical challenges. References: [1] Rotating clusters in phase-lagged Kuramoto oscillators with higher-order interaction, B Moyal, P Rajwani, S Dutta, S Jalan, PRE 109 (3), 034211 (2024). [2] Finite-size effect in Kuramoto phase oscillators with higher-order interactions, Ayushi Suman, S. Jalan, Chaos, 34 (10) (2024) [3] Synchronization transitions in adaptive KuramotoSakaguchi oscillators with higher-order interaction, S. A Sharma, P Rajwani, S Jalan, Chaos (8) (2024) [4] Prolonged hysteresis in the Kuramoto model with inertia and higher-order interactions, NG Sabhahit, AS Khurd, S Jalan, PRE 109 (2), 024212 (2024).

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MS188

Chimera Patterns under the Local Lvy Noise Excitation Based on Deep Learning

Nonlocally coupled oscillator systems can exhibit intricate spatiotemporal patterns known as chimera states, characterized by the coexistence of spatially coherent and incoherent domains. We have identified a novel manifestation of these states in nonlocally coupled Fitz Hugh-Nagumo ring network with the introduction of local Lvy noise. To address the challenges of low accuracy and poor stability in traditional algorithms when dealing with systems exhibiting rapid oscillatory behavior, we propose a deep learning-based solution method. Our simulation findings substantiate the efficacy of this algorithm. Furthermore, we observe that the characteristic exponent and skewness parameter of Lvy noise significantly impact the network dynamics behaviors. Additionally, we investigate the effects of coupling range and noise intensity, as well as coupling strength and noise intensity, on the network's dynamical behaviors.

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MS189

Altruism and Energy Flow in Dynamic Beehive Models

This work explores the relationship between altruism and the genetic system of arrhenotoky through an evolutionary game theory (EGT)-inspired lens, using a dynamic model of beehive populations. Arrhenotoky is a form of asexual reproduction in which unfertilized eggs become males while fertilized eggs develop into females, leading to unusual patterns of genetic relatedness between family members. This mode of reproduction occurs in insects such as the *Hymenoptera*, including bees. In the hive environment, bees often display altruistic behavior, or actions taken by an organism that reduce its own fitness to increase the fitness of others. Eusociality, an elaborate form of social organization characterized by complex and altruistic social behaviors, is also observed in bees. To explore the interplay between altruism and the reproductive patterns of arrhenotoky, we employ a population dynamics model to simulate beehive populations over a range of parameters, controlling for altruism in workers and the queen. Our results show that altruistic behaviors are essential for beehive success, with optimal worker altruism corresponding to the division of labor observed in eusocial species. Furthermore, we find that modest altruism from the queen is also vital for hive survival, emphasizing the delicate balance that can exist in these complex social systems. Our findings shed light on the co-evolution of altruism, arrhenotoky, and eusociality in the natural world.

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MS189

Eco-Evolutionary Game Dynamics in a Network

with Two Communities

Recent developments of eco-evolutionary models have shown that evolving feedbacks between behavioral strategies and the environment of game interactions, leading to changes in the underlying payoff matrix, can impact the underlying population dynamics in various manners. We propose and analyze an eco-evolutionary game dynamics model on a network with two communities such that players interact with other players in the same community and those in the opposite community at different rates. In our model, we consider two-person matrix games with pairwise interactions occurring on individual edges and assume that the environmental state depends on edges rather than on nodes or being globally shared in the population. We analytically determine the equilibria and their stability under a symmetric population structure assumption, and we also numerically study the replicator dynamics of the general model. The model shows rich dynamical behavior, such as multiple transcritical bifurcations, multistability, and anti-synchronous oscillations. Our work offers insights into understanding how the presence of community structure impacts the eco-evolutionary dynamics within and between niches.

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MS189

The Population Lotto Game: How Strategic Resource Allocation Structures Non-Transitive Outcomes in Pairwise Competitions

In order to understand if and how strategic resource allocation can constrain the structure of pair-wise competition outcomes in human competitions we introduce a new multiplayer resource allocation game, the Population Lotto Game. This new game allows agents to allocate their resources across a continuum of possible specializations. While this game allows non-transitive cycles between players, we show that the Nash equilibrium of the game also forms a hierarchical structure between discrete 'leagues' based on their different resource budgets, with potential sub-league structure and/or non-transitive cycles inside individual leagues. We provide an algorithm that can find a particular Nash equilibrium for any finite set of discrete sub-population sizes and budgets. Further, our algorithm finds the unique Nash equilibrium that remains stable for the subset of players with budgets below any threshold.

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MS189

Spatial Pattern Formation in Eco-Evolutionary Games with Environment-Driven Motion

The sustainable management of common resources often leads to a social dilemma known as the tragedy of the commons: individuals benefit from rapid extraction of resources, while communities as a whole benefit from more sustainable extraction strategies. In this talk, we explore a PDE model of evolutionary game theory with environmental feedback, describing how the spatial distribution of resource extraction strategies and environmental resources evolve due to reaction terms describing eco-evolutionary game-theoretic dynamics and spatial terms describing diffusion of environmental resources and directed motion of resource harvesters towards regions of greater environmental quality. Through linear stability, we show that this biased motion towards higher-quality environments can lead to spatial patterns in the distribution of extraction strategies, creating local regions with improved environmental quality and increase payoff for resource extractors. However, by measuring the average payoff and environmental quality across the spatial domain, we see that this pattern-forming mechanism can actually decrease the overall success of the population relative to the equilibrium outcome in the absence of spatial motion. This suggests that environmental-driven motion can produce a spatial social dilemma, in which biased motion towards more beneficial regions can produce emergent patterns featuring a worse overall environment for the population.

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MS190

Heat Waves and Zombie Fires: Rate-induced Phase-tipping in Fast-slow Nnonautonomous Systems

Zombie fires are an interesting phenomenon in peatlands, where fires disappear from the surface in winter while smoldering underground, only to reappear the following spring with the seasonal rise in atmospheric temperature. In this talk, we present a conceptual model of peat soil combustion, that incorporates seasonal variations in atmospheric temperature as well as temperature anomalies due to heat waves. We use experimental data to fine-tune the parameters of our model and show that a heat wave can cause the bioactive soil to transition from its cold base state to one of two hot metastable states. The first is a fire-friendly state, where the temperature of the peat is below combustion but high enough to sustain high levels of microbial bioactivity (or respiration), releasing large amounts of carbon into the atmosphere over a prolonged period of a few years to a decade. The second is a zombie fire state, where the organic content of the peat burns at a very high temperature and for a shorter period of one to a few years. We then combine concepts from geometric singular perturbation theory with a special compactification technique and our understanding of rate-induced phase-tipping from limit cycle attractors to explain these transitions.

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MS190

Rate Induced Tipping in a Moving Habitat

In this talk, we present numerical evidence of a condition conjectured to characterize rate-induced tipping phenomena in a reaction-diffusion model of species persistence under shifting habitat conditions. The model is a scalar reaction-diffusion equation with a spatially heterogeneous reaction term representing a localized favorable habitat zone. We demonstrate that above some critical habitat displacement value, rate-induced tipping occurs.

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MS190

The Impact of Rainfall Variability on the Resilience of Vegetation Patterns in Dryland Ecosystems

Desert ecosystems have been characterized by Noy-Meir (1973) as "water-controlled ecosystems with infrequent, discrete and largely unpredictable water inputs," with the limiting resource of water arriving in short-lived pulses. These dry climates are known to support regular, large-scale patterns of vegetation growth organized into evenly spaced bands that are separated by swaths of bare soil, and studies suggest that this may provide improved resilience to drought. I will present a modeling framework for vegetation pattern formation in drylands that treats storms as instantaneous kicks to the soil water, which then interacts with vegetation during the long dry periods between the storms. The spatial profiles of the soil water kicks capture positive feedbacks in the storm-level hydrology that act to concentrate water within the vegetation bands. This flow-kick model predicts that variance in rainfall introduced through randomness in the timing and magnitude of water input from storms decreases the parameter range over which patterns appear and may therefore negatively impact ecosystem resilience.

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MS191

Pedestrian Models with Congestion

In this talk, we investigate the dissipative Aw-Rascle system as a macroscopic model for pedestrian dynamics. The model incorporates a congestion term, represented by a singular diffusion, to impose capacity constraints on crowd density while simulating steering behavior. We present a semi-implicit, structure-preserving, and asymptotic-preserving numerical scheme that efficiently handles the solution of the model across different scenarios. The talk will highlight the first numerical simulations of the dissipative Aw-Rascle system in one and two dimensions, and demonstrate the efficiency of the scheme through various numerical experiments. Finally, we validate the model by showing that it accurately captures the fundamental diagram of pedestrian flow, confirming its potential as a robust tool for simulating pedestrian dynamics.

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MS191

Overview on Constraints Mean Field Games and New Perspectives

In this talk I will give an overview of mean field games with state constraints. Interest in these types of problems has been growing rapidly in recent years. The main motivation is that state constraints appear very natural in several applications (e.g., pediatric dynamics and macroeconomic models). Unfortunately, the state constraints introduce several difficulties in the definition of the equilibrium and the solution of the problem, which cannot be defined in terms of the solution of a PDE system as in the absence of constraints. Therefore, we attack the problem by considering a relaxed version of it, for which the existence of equilibria can be proved by set-valued fixed-point arguments. By analyzing the regularity and sensitivity with respect to space variables of the relaxed solution, we will show that it satisfies the Mean Field Games system in an appropriate pointwise sense.

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MS191

Topological Swarming Dynamics and Emergent Leader Behavior in Self-Organizing Biological Systems

The collective behavior of animals, such as bird flocks, fish schools, and insect swarms, is a key topic in Mathematical Biology. Here, we examine a model for the collective motion of birds, where sudden spontaneous changes in direction occur without predator influence. In this model, any bird can initiate a turn, temporarily becoming a leader whose influence impacts its nearest neighbors in the follower state. Once an agent becomes a leader, it initiates a direction change that spreads through the flock. This leadership is transient, as agents can switch roles over time, between leader and follower states. The model can incorporate food sources, visible only to agents in the leader state, to reflect realistic foraging dynamics. We derive a kinetic description of the agents' distribution from the microscopic model, combining position and velocity updates through binary interaction rules with dynamic label changes between leader and follower states. To solve the model numerically, we employ a Monte Carlo method to simulate the evolution of labels and a Nanbu algorithm for interactions. To approximate the topological neighborhood, we replace the exhaustive search with a k-nearest neighbor approach, reducing computational complexity from quadratic to logarithmic. Finally, we present various numerical tests to validate the model's predictions.

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MS191

The Effect of Domain Growth on Pattern Formation: a Systematic Study Via Amplitude Equations

Theories of localized pattern formation are important for understanding a wide range of natural patterns, but only recently has the ubiquitous effect of domain growth been included in such studies. Here we extend recent work on pattern formation on slowly growing domains by identifying the corresponding amplitude equations near the bifurcation point, i.e. near the boundary of Turing space. By a systematic treatment of the three crucial timescales involved, the reaction timescale, the diffusion timescale and the growth timescale, we show how and when the effect of the growing domain becomes important for the system response. Using the weakly nonlinear analysis, we also evaluate the effect of growth on the observed pattern. New implications are revealed that have not been observed before, including the discussion of what is the relevant reference state (which is the homogeneous steady state in classical Turing analysis). Further, the effect of growth depends on the interplay of growth and reaction kinetics in a complex way and we obtain new effects of the domain growth on the instability condition including the speed of travelling wave propagation. As a final example, for some growth we observe it's impact even for short times while for others the effect on the size of Turing domain can be substantially different from the fixed domain case.

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MS192

Exploring Inertial Effects on Swimming Protist Colonies: A Reduced Model Approach

The evolution from unicellular to multicellular organisms represents a pivotal event in metazoan history, and understanding the hydrodynamics of swimming protist colonies sheds light on this transition. Ideally, modeling these colonies would involve detailed representations of cell morphology and flagellar dynamics, though computational costs make this challenging. Our previous model used an optimized Stokeslet method to model choanoflagellate colonies under the Stokes flow assumption. Although the typical length scales and colony speeds are small enough that the Stokes equations apply, PIV images from Koehl Lab - UC Berkeley reveal larger flow velocities near the colony, resulting in a higher Reynolds number in those regions. This suggests that inertial effects may contribute to the local dynamics of the colony. In this work, we extend our previous work to include inertial effects. We consider a two-dimensional colony within a periodic box and propose a novel singularity representation for individual cells in the Navier-Stokes equations. We demonstrate that for sufficiently small Reynolds number, this individual cell model exhibits the behavior similar to that in the Stokes regime. Building on this, we propose a colony model that maintains a structure observed experimentally and investigate how small amounts of inertia impact the colony's hydrodynamic performance.

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MS192

A New Regularised Line Delta Source

The immersed boundary method uses the Dirac delta distribution to interpolate singular forces that arise in fluid-structure interaction problems containing flexible 1D structures that are defined along moving curves. Most numerical approaches regularise the Dirac delta distribution by discretising the interface at a sequence of points and then introducing a regularisation of the Dirac delta point-source over a finite support radius of size H. The corresponding delta-forcing term is then interpolated onto an underlying fluid grid (with spacing denoted h) using appropriate quadratures. We derive an analytical form for a regularised line source that can be implemented in an immersed boundary framework. This regularisation is constructed independently of the numerical method and constrained to satisfy moment properties of the Dirac delta line source distribution. The regularisation can be chosen up to a predetermined spatial order of accuracy with respect to its support H. Using both finite element and spectral approximations of a 3D test problem, we compare the results for our regularised line source to that from the usual point-delta approximation and observe that the new regularisation has much smaller numerical errors. This improvement comes from capturing the invariance of the line source along the direction of the immersed structure, which cannot be done for point approximations. These conclusions are supported by a careful convergence analysis in both h and H.

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MS192

AdaptiveRegularization of Rough Linear Functionals for Nonconforming FEM

Rough linear functionals (such as Dirac Delta distributions) often appear on the right-hand side of variational formulations of PDEs. As they live in negative Sobolev spaces, they dramatically affect adaptive finite element procedures to approximate the solution of a given PDE. Furthermore, in the case of nonconforming (or broken) test spaces, rough functionals could not even belong to the dual of such a test space. To overcome this drawback, we propose an alternative that, in the first step, computes a projection of the rough functional over piecewise polynomial spaces, up to a desired precision in a negative norm sense, using either conforming or nonconforming test spaces. The projection (being L^p-regular) is then used as the right-hand side of a regularized PDE problem for which adaptive nonconforming methodologies are perfectly well-defined and converge. An error analysis of the proposed methodology will be shown, together with numerical experiments.

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MS192

Stokeslets and Other-Lets in the Biomechanics of Reproduction

Flagella are thin structures required for sexual reproduction in many species. To model the motion of these structures in biologically-relevant scenarios, approximating singular sources terms along a curve in is necessary. Because of the low Reynolds number environment involved at these scales, the fluid mechanical problem can be solved using Stokeslets, rotlets, and other "lets" that enable us to model three-dimensional motions. In this talk, we will introduce these "lets" and discuss their impact on models in 2D versus 3D frameworks in the context of reproduction and sperm motility.

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MS193

Deep Neural Networks on Diffeomorphism Groups for Shape Analysis

Shape analysis is a framework for treating complex data and obtaining metrics on spaces of data. Examples are spaces of unparametrized curves, time-signals and surfaces. In this talk we discuss structure preservation and deep learning for classifying, analysing and manipulating shapes. A computationally demanding task is the computation of optimal reparametrizations leading to an optimisation problem on the infinite dimensional group of orientation preserving diffeomorphisms. We propose to approximate diffeomorphisms with ResNets and tangent space paremetrisations, and prove expressivity results. Another interesting challenge is that of learning dynamical systems from data e.g. motion capturing data.

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MS193

Some Recent Developments in the Stability of Dynamical Systems Based Neural Networks

We consider neural networks to be dynamical systems. The networks are interpreted as discretization of differential equations. Robustness with respect to adversarial attacks can be improved by imposing stability restrictions both to the continuous model and to the discretization. Non-expansiveness of the exact flow can be controlled by imposing various types of monotonicity conditions on the underlying vector field. But conditions must be added to control the discretization as well; one can achieve this by restricting the type of discretization method and the time step. Since the most popular layer maps in machine learning come from explicit schemes, we shall derive rigorous bounds for the step size to obtain non-expansive method maps. This results in a practical adaptive step size algorithm that we demonstrate for some denoising problems. The next step in this research is to repeat the strategy for obtaining non-expansive layer maps in the case that our data and latent spaces take values in Riemannian manifolds. We have proved that for certain discretization methods based on geodesics, their unconditionally non-expansive behavior depends on the sectional curvature of the manifold. Now, we shall also consider explicit geodesics schemes and present the first results on how the step size must be limited to obtain non-expansive maps on positively curved Riemannian manifolds.

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MS193

Reimaging Gradient Descent: Large Stepsize, Oscillation, and Acceleration

Gradient descent (GD) and its variants are pivotal in machine learning. Conventional wisdom suggests smaller stepsizes for stability, yet in practice, larger stepsizes often yield faster convergence, despite initial instability. In this talk, I will explain how large stepsizes provably accelerate GD for logistic regression on separable data in three settings. We start with logistic regression, a convex but non-strongly convex problem. We show that GD with a large stepsize attains an ϵ-risk in $O(1/\sqrt{\epsilon})$ steps. This matches the accelerated step complexity of Nesterov momentum and improves the classical $O(1/\epsilon)$ step complexity for GD with a small stepsize. We then consider ℓ_2-regularized logistic regression with regularization strength λ, a strongly convex problem with condition number $\Theta(1/\lambda)$. We show GD with a large stepsize attains an ϵ-excess risk in $O(1/\sqrt{\lambda}\ln(1/\epsilon))$ steps. This, again, matches Nesterov momentum and improves the $O(1/\lambda\ln(1/\epsilon))$ step complexity for GD with a small stepsize. Finally, we consider the task of finding a linear separator of a linearly separable dataset with margin γ. We show that, with large and adaptive stepsizes, GD solves this task in $1/\gamma^2$ steps by minimizing the logistic risk. We further show this step complexity is minimax optimal for all first-order methods, and cannot be achieved by GD with small stepsies. The talk is based on a sequence of papers in collaboration with Peter Bartlett, Matus Telgarsky, Bin Yu, Ruiqi Zhang, Licong Lin, and Pierre Marion.

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MS193

Dynamical-adapted Regularization for Autoencoder with the Observed SDE Dynamics

We propose two dynamical adapted regularization terms to improve the accuracy and generalization of learning stochastic dynamics on the manifold. We assume an SDE solver is available and one has access to estimates of the extrinsic dynamical quantities such as the point on manifold with its associated drift vector field and covariance matrix. We add two regularization terms inspired from Itô formula and Manifold, to the AE loss. We will demonstrate with these two regularization terms, the learnt dynamics generalize better with benchmark examples.

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MS194

Understanding Tonic-Clonic Seizure Transitions As Secondary Bifurcations in a Neural Field Model

Epilepsy is a dynamic complex disease involving a paroxysmal change in the activity of millions of neurons, often resulting in seizures. Tonic-clonic seizures are a particularly important class of these and have previously been theorised to arise in systems with an instability from one temporal rhythm to another via a quasi-periodic transition. We show that a recently introduced class of next generation neural field models has a sufficiently rich bifurcation structure to support such behaviour. A linear stability analysis of the space-clamped model is used to uncover the conditions for a Hopf-Hopf bifurcation whereby two incommensurate frequencies can be excited. This is used to seed a more exhaustive numerical bifurcation analysis that highlights the preponderance of the model to generate torus bifurcations. Since the neural field model is derived from a biophysically meaningful spiking tissue model we are able to highlight the neurobiological mechanisms that can underpin tonic-clonic seizures as they relate to levels of excitability, electrical and chemical synaptic coupling, and the speed of action potential propagation. We further show how spatio-temporal patterns of activity can evolve in the fully nonlinear regime using direct numerical simulations far from a Turing bifurcation.

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MS194

Computing Resonance in Brain Networks to Localize Epileptic Seizures

Medically-refractory epilepsy (MRE) is a devastating neurological disease that is defined by recurrent and unprovoked seizures that are insufficiently controlled by anti-epileptic medications. If the seizures are originating from a specific region of the brain, surgical removal or stimulation of the epileptogenic region can be an effective therapy for these patients. The accurate localization of the seizure onset zone (SOZ) is critical for surgical success, but localizing the SOZ is difficult and surgical success rates vary from 34–70%. In this talk, I will describe a study that aims to improve seizure onset localization and expedite the intracranial monitoring process by employing dynamical network models that investigate resonance phenomena the patient's epileptogenic network with recordings obtained during single-pulse electrical stimulation (SPES). We hypothesize that a dynamical quantification of the connectivity networks derived from the evoked responses induced by SPES could also be used to accurately localize the SOZ and guide clinicians in eliciting native seizures with electrical stimulation when stimulating at resonant frequencies. I will give an overview of these dynamical network techniques and describe their potential impact in the clinical treatment of medically-refractory epilepsy.

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MS194

Circadian Dynamics and Causality in Epilepsy

Our body clock follows a 24-hour circadian rhythm, and is crucial for regulating sleep, hormones, metabolism, and mood. Its disruption is linked to conditions like depression, obesity, and epilepsy. Laboratory studies, where external factors like light and meal timing are tightly controlled, have advanced our understanding of circadian biology. However, we still lack insights into what a healthy body clock looks like in real-world conditions and how disruptions impact health. To capture human behaviour and physiology over weeks in real-world settings, we will leverage the latest developments in mobile and wearable technologies. Mathematically analysing this circadian system is challenging. We need to identify latent cyclical patterns and causal relationships between different sensor streams and physiological variables. My talk will highlight a few recent attempts and results we obtained in tackling this challenge, both in health and in epilepsy.

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MS195

Passivity-Based Control with SINDy

IDA-PBC (Interconnection and Damping Assignment) is a successful nonlinear control technique that attempts at shaping a port-Hamiltonian (pH) structure for a controlled physical plant. In particular, pH formulations are interesting because they encode key behaviors, e.g., stability, of nonlinear physical systems. While IDA-PBC has been theoretically applied to a large range of systems, its practical implementation remains limited, often confined to academic examples. This limitation arises from the complexity of solving a set of partial differential equations (PDEs) referred to as matching conditions, which is extremely challenging, especially for complex physical systems. We introduce a novel numerical approach for solving the IDA-PBC control problem using the sparse dictionary learning methods, originally developed for the sparse identification of nonlinear systems (SINDy). We use a library of dictionary (nonlinear) functions to learn interpretable closed-form expressions for the desired controllers, making the IDA-PBC method applicable to complex applications, such as periodic oscillations.

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MS195

Data-Driven System Analysis Using Polynomial Optimization and the Koopman Operator

Many important statements about dynamical systems can be proven by finding scalar-valued auxiliary functions whose time evolution along trajectories obeys certain pointwise inequality that imply the desired result. The most familiar of these auxiliary functions is a Lyapunov function to prove steady-state stability, but such functions can also be used to bound averages of ergodic systems, define trapping boundaries, and so much more. In this talk I will highlight a method of identifying auxiliary functions from data using polynomial optimization. The method leverages recent advances in approximating the Koopman operator from data, so-called extended dynamic mode decomposition, to provide system-level information without system identification. The result is a flexible, data-driven, model-agnostic computational method that does not require explicit model discovery. Furthermore, it can be applied to data generated through deterministic or stochastic processes with no prior adjustments to the implementation. It can be used to bound quantities of interest, develop optimal state-dependent feedback controllers, and discover invariant measures.

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MS195

Conformal Prediction for Time Series with Ensemble SINDy

The sparse identification of nonlinear dynamics (SINDy) algorithm discovers dynamical system models that are interpretable and generalizable. This is important to make the discovered models trustworthy, especially for models deployed in high-consequence and safety-critical environments. Additionally, models deployed in these environments must provide safety guarantees, and guarantees on model stability and robustness. Recent extensions of SINDy provide tools for estimating these guarantees in the model discovery procedure through uncertainty quantification and conformal prediction. In this talk, we present an extension of SINDy using ensemble learning (E-SINDy), which performs computationally efficient uncertainty quantification. We discuss connections between E-SINDy and a Bayesian model discovery extension of SINDy, and show that E-SINDy provides valid uncertainty quantification with correct variable selection and guaranteed convergence. Finally, we show how E-SINDy can be used with conformal prediction methods to provide coverage guarantees of prediction intervals, and how they can be used to obtain safety guarantees in trajectory prediction algorithms for unknown moving obstacles.

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MS195

Symmetry Enforcement, Discovery, and Promotion for Machine Learning Applications in Engineering

For centuries, symmetry has been a powerful tool for both (i) simplifying complex phenomena through dimensionality reduction, and (ii) mapping a particular solution to a wider class of solutions through application of the symmetry. In the 21st century, we are analogously seeing the effects of how symmetry can play a role in reducing the amount of data needed to train machine learning models and improve their ability to generalize to unseen data. In this talk, we provide a unifying framework for incorporating symmetry into machine learning models in three ways: (1) enforcing known symmetry when training a model; (2) discovering unknown symmetries of a given model or data set; and (3) promoting symmetry during training by learning a model that breaks symmetries within a specified group of candidates when there is sufficient evidence in the data. These three tasks can all be cast within a common mathematical framework where symmetry can be studied through the null-space of a bilinear operator. In particular, we propose a novel way of promoting symmetry through a convex regularization function. We conclude by demonstrating this methodology on a variety of engineering applications.

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MS196

Local Control for the Collective Dynamics of Self-Propelled Particles

Using a paradigmatic model of self-propelled, interacting particles, we demonstrate that local accelerations at the individual particle level can induce transitions between distinct collective dynamics, enabling a control mechanism. Our findings reveal that the capacity to trigger these transitions is distributed hierarchically among the particles, forming distinct spatial patterns within the collective. These particle hierarchies provide decentralized control potential for natural and artificial systems of interacting elements. Furthermore, an analysis of the transient dynamics during these transitions uncovers chaotic behavior linked to unstable chaotic sets, which play a key role in mediating the control process.

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MS196

Transient Chaos in Cardiac Excitable Media

Chaotic spatio-temporal dynamics in excitable media such as cardiac tissue is often not permanent but limited in time. In this contribution, we discuss the influence of heterogeneities, stochastic perturbations, and feedback control on the mean lifetime of such chaotic transients. Using simulations with the Aliev-Panfilov and the Fenton-Karma model, we show that these perturbations can (significantly) prolong or shorten the duration of chaotic transients and may also lead to persistent chaos or stable periodic wave patterns.

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MS196

Noise Placement and Color and Their Influence on Ecological Transients

Long transient dynamics have recently been studied extensively in ecology, but the impact of noise on their duration is not well understood. We consider various options for how to include stochasticity in a model with long transients. We also explore the impact that the noise quality (e.g., the noise "color") has on the long transient duration.

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MS196

Analysis of Long Transient Dynamics in a Predator-prey Model Featuring Two Timescales

The leading role of long transient dynamics in ecological timescales can be very important in explaining regime shifts. In this talk, I will consider a three-dimensional predator-prey model featuring two timescales with explicit interference competition between the predators. I will consider two different scenarios in a parameter regime near *singular Hopf bifurcation* of the coexistence equilibrium point. In one case, the system exhibits bistability between a periodic attractor and a boundary equilibrium state with long transients characterized by rapid small-amplitude oscillations with slow variation in amplitudes, while in the other, the system exhibits chaotic *mixed-mode oscillations* as long transients before approaching a stable limit cycle. I will address the underlying mechanism leading to the long transients and use tools from singular perturbation theory to analyze them. The analysis is then used to devise early warning signals of dramatic population transitions in the system.

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MS197

Swimming Behavior of Bacteria Near Surfaces Depends on Their Length

It is well known that flagellated bacteria swim in circular trajectories near surfaces due to increased hydrodynamic drag on the counter-rotating flagella and cell body. Little work, however, has been done to investigate the effects of cell length on these circular trajectories and overall swimmer behavior near surfaces. We study this effect using Enterobacter sp. SM3, which are peritrichous and rod-like bacteria that can grow to variable length. We find that the average linear speed, angular speed, and curvature of the near-surface circular trajectories all depend on the cell length. In addition, we construct a computational model for spherocylinder-shaped micro-swimmers that accounts for near-surface hydrodynamic interactions as well as to Brownian noise. The simulations echo the experimental findings and accentuate the role of the swimmer morphology in its near-surface dynamics.

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MS197

Transport and Non-equilibrium Diffusion dDriven by Collectively Moving Microswimmers

Transport and diffusion are essential in biological processes, generating molecular fluxes that sustain life. Classically, these fluxes are described by Ficks laws for random walks near thermal equilibrium. However, active systems locally inject energy into their surrounding medium, driving non-equilibrium diffusion for which a general theory remains elusive. We distinguish between two types of systems: active baths and active carpets. In the former, suspensions of active particles can enhance mixing and transport cargo using collective hydrodynamic entrainment. For active carpets, biological activity is highly concentrated on surfaces, such as biofilms. They can generate flows to attract nutrients from the bulk, by clustering and forming topological defects. Moreover, active carpets produce anisotropic and space-dependent diffusion, for which we derived generalized Ficks laws. We solved two archetypal problems using these laws: First, considering sedimentation towards an active carpet, we find a self-cleaning effect where surface-driven fluctuations can repel particles. Second, considering diffusion from a source to an active sink, say nutrient capture by suspension feeders, we derived the enhanced molecular flux compared to thermal diffusion. Hence, our results could elucidate specific non-equilibrium properties of active coating materials and life at interfaces.

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MS197

Experimental Studies of Chaotic Behavior, Dynamic Trapping and Anomalous Diffusion of Swimming Microbes in Laminar Flows

We present studies of the motion of swimming *Tetraselmis* microbes in a laminar, two-dimensional flow vortex chain flow. Simulations show that a smooth-swimming microbe in this flow can undergo either chaotic or ordered trajectories, depending on the swimming speed v_0 and the location of the microbe in the flow. The vortex chain flow in the experiments is generated by magnetohydrodynamic forcing, and the *Tetraselmis* microbes are imaged with an inverted microscope and tracked individually. Apparently-chaotic trajectories are prevalent in the experiments. Microbes swimming with small v_0 trap dynamically to ghosts of islands of ordered trajectories, resulting in long-range transport that is sub-diffusive. The trapping is absent for faster-swimming microbes, resulting in diffusive long-range transport. We also show experimental evidence of local barriers due to swimming invariant manifolds that impede the motion of microbes in the flow.

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MS197

Probing the Motility, Mixing, and Pattern Development at the Bacterial Swarm Front

Swarming is a prevalent form of bacterial collective motility. We study a particular species of bacteria, Enterobacter sp. SM3, which manifests strong swarming behavior. One ongoing project is focused on probing the swarm front on agar, a semi-solid substrate that provides nutrients for bacterial growth. By depositing a fluid droplet at the swarm edge, a monolayer of swarming bacteria is observed. We track the motility of these swarming bacteria, to analyze their velocities, orientations, and mean square displacements within and outside dynamic packs they form. We find that the air-liquid and liquid-solid interfacial confinements profoundly influence the swarming behavior, particularly at the swarm edge where the thin fluid layer is pinned. Recognizing this physical effect, we incorporate mucin, the major component of mucus found on airway and intestinal surfaces, into an agar gel to test its effects on the swarming motility of SM3. We find that mucin promotes swarming by inhibiting contact line pinning and making the agar surface more slippery. Through these experiments on bacterial swarming motility, we gain new insights on active matter collective properties.The knowledge and insights gained from the bacterial swarming research may also lead to important biomedical and environmental applications.

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MS198

Listening to the Atmosphere: Using Infrasound Waves to Constrain Upper Atmospheric Winds

The stratosphere and mesosphere lack the observational coverage that the troposphere enjoys. The processes in those upper layers have an impact on the weather at the Earth's surface at the medium range, so any information on them can improve forecasts in this range. In this talk we explain how to take advantage of existing indirect observations of these layers using Data Assimilation. Natural and antropogenic events in the Earth's surface can generate infrasound waves which travel long distances through the atmosphere. When the paths have a vertical component, they can effectively probe the atmopshere in a tomographic fashion. For point-source emissions, three observations can be recorded using acoustic arrays: travel time, change in backazimuth angle, and apparent velocity. We use the Modulated Ensemble Transform Kalman Filter to assimilate these observations into atmospheric profiles and infer updates to both horizontal winds and temperature at different vertical levels. Our results show a promising path towards an eventual inclusion of infrasound-related observations in Numerical Weather Prediction.

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MS198

Parameter Estimation using Sequential Data As-

similation

This presentation delves into sequential Bayesian methods for estimating Earth system parameters in conjunction with prognostic state variables. By leveraging an extended state approach, we build state and parameter covariances using ensembles of model and parameter realizations. We will demonstrate the application of the ensemble Kalman filter and smoother in solving various parameter estimation problems, ranging from simplified toy models to complex Earth system models. Additionally, techniques for parameter inflation and localization will be explored. The talk will further examine the spatial configurations of parameters, proposing strategies for efficiently estimating both global and local parameters.

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MS198

Numerical Results of Nudging the Generalized Surface Quasigeostrophic Equations

We present numerical results for the nudging (aka AOT) algorithm applied to the subcritical surface quasigeostrophic equation (SQG). An empirically determined resolution for the data is compared to the sufficient condition proved in Adv. Nonlinear Stud. 2017; 17 (1):167-192. The latter expresses the resolution in a law, the power of which depends on the power, α, on the fractional laplacian. We also test the algorithm on the generalized SQG, a two parameter family where both α and β, a measure of the singularity in the constitutive law, are varied.

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MS199

Chaotic Behavior in Time-dependent Vaccination Campaign

Infectious diseases are illnesses caused by pathogens, such as bacteria and viruses, and transmitted between hosts by various mechanisms. Vaccination is one of the most efficient ways to control the spread of infectious diseases. Mathematical models in epidemiology have been proposed to describe the transmission and spread of infectious diseases. They are powerful tools to study strategies for epidemic spread, such as vaccination campaigns. This work proposed an SEIRS (susceptible-exposed-infected-recovered-susceptible) model with time-dependent vaccination rates. Depending on the parameters, we observe periodic and chaotic behaviors. In the parameter space, we verify islands of periodicity within a chaotic sea, known as shrimps. We show that the controlled chaotic structures can become periodic structures. Therefore, we demonstrate that a time-dependent vaccination campaign on the dynamical behavior of a seasonal forced SEIRS model can control chaotic bands.

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MS199

Low-Order Solar Dynamo Model under Linear Forcing

We replace magnetohydrodynamic (MHD) simulations, commonly used to model solar activity, with a low-order dissipative dynamo model. This approach incorporates the so-called Lorentz force feedback, which drives the meridional flow in MHD models and results in cyclic polarity reversals in the calculations. The model describes the dynamic behavior of the Suns toroidal and poloidal magnetic fields, exhibiting a wide range of behaviors depending on the system parameters, from regular periodic motion through period-doubling bifurcations to chaotic properties. In our study, we investigate the dynamics of these two components of the Sun's magnetic field when the amplitude of the Lorentz force feedback varies over time, either continuously or, in more realistic scenarios, randomly. This introduces an explicit time-dependence into what was originally a time-independent dynamic, resulting in a nonautonomous system. In such cases, traditional methods of dynamical systems theory, typically used to study chaotic behavior, are not applicable. Instead, recently developed approaches involving time-dependent phase space structures (e.g., snapshot attractors) provide an accurate description of the behavior of nonautonomous systems. In this work, we map the phase space of the magnetic field components in the presence of multiple attractors and offer a quantitative description of the dynamical effects of the time-varying parameter.

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MS199

Magnetic Structures in the Explicitly Time-Dependent Nontwist Map

We investigate how the magnetic structures of the plasma change in a large aspect ratio tokamak perturbed by an ergodic magnetic limiter, when a system parameter is non-adiabatically varied in time. We model such a scenario by considering the Ullmann-Caldas nontwist map, where we introduce an explicit time-dependence to the ratio of the limiter and plasma currents. We apply the tools developed recently in the field of chaotic Hamiltonian systems subjected to parameter drift. Namely, we follow trajectory ensembles initially forming KAM tori and island chains in the autonomous configuration space. With a varying parameter, these ensembles, called snapshot tori, develop time-dependent shapes. An analysis of the time evolution of the average distance of point pairs in such an ensemble reveals that snapshot tori go through a transition to chaos, with a positive Lyapunov exponent. We find empirical power-law relationships between both the Lyapunov exponent and the beginning of the transition to chaos, as a function of the rate of the drift, with the former showing an increasing, and the latter a decreasing trend. We conclude that, in general, coherent tori and magnetic islands tend to break up and become chaotic as the perturbation increases, similarly to the case of subsequent constant perturbations. However, because of the continuous drift, some structures can persist longer, and exist even at parameter values where they would not be observable in the constant perturbation case.

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MS199

Predictability of Tipping in a Climate Model Featuring a Multistable Ocean Crculation

We study the dynamics of a global ocean model, featuring a complex multistability of the Atlantic circulation, under different time-varying forcings. Transitions from a state of vigorous, present-day Atlantic Meridional Overturning Circulation to a state of collapsed circulation are induced by the influence of climate change or stochastic perturbations. The predictability of transitions, and thus of the future climate state, can be limited, due to chaotic dynamics and non-autonomous dynamical effects. The simulations are used to argue for two points that we believe are more generally applicable for multistable, non-autonomous complex systems: a) Due to partial tipping (a splitting of an ensemble of initial conditions under time-varying forcing) in a chaotic system, there is a loss of predictability of the future attractor. But for systems that are stationary in the past limit, a new type of predictability arises, by which the probabilities of tipping to different future states can be calculated using ensemble simulations with arbitrary initial conditions. b) When the system is subjected to stochastic forcing and a monotonic parameter shift, an impending crisis may be better predicted by early-warning signals that are designed from knowledge of the transition instanton and/or an edge state.

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MS200

Rational Eigenfunctions of KPI Equation

TBA

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MS200

Malmquist-Takenaka Approximation of Rational PDE Solutions

Rational solutions occur in a variety of interesting and physically important partial differential equation (PDE) models. Numerically approximating these solutions on the real line using standard Fourier methods is challenging due to their algebraically slow decay rate. An alternate basis of orthogonal rational functions, known as the Malmquist-Takenaka functions, is proposed to approximate this class of solution. For rational solutions, these approximations converge spectrally (exponentially) fast. A spectral method for linear and nonlinear PDEs will be introduced; its stability and accuracy will be discussed.

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MS200

The Stability of Swimmers Interacting Via Vortex Sheet Waves

The effect of hydrodynamic interactions on the schooling behavior of animal collectives is studied via a model of multiple flapping plates (or swimmers) in an inviscid, incompressible fluid. The plates move vertically with a prescribed oscillatory motion, and horizontally via a self-induced thrust. Imposition of the Kutta condition at the trailing edge of each plate generates a shed vortex sheet, which then interacts with the other swimmers. As either the number of plates increases or the oscillation amplitude decreases, the schooling modes are found to destabilize via oscillations that propagate downstream from the leader and cause collisions between the plates, an instability that is similar to that observed in recent experiments on flapping wings in a water tank. A simple control mechanism is introduced and shown to stabilize the equilibrium configurations, with a remarkable impact on the regularity of the vortex pattern in the wake.

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MS201

Retrospective on the Control of Discontinuity-induced Bifurcations of Periodic Orbits in Vibro-impact Systems

This talk reviews several results in the literature that demonstrate how feedback control may be applied to an impact discontinuity in a vibro-impact system in order to stabilize the local dynamics near grazing bifurcations. The goal of such control is to ensure that the onset of low-velocity collisions with a rigid obstacle does not result in an uncontrolled transition to dynamics with high-contact-velocity collisions. The relevant theory builds on a local analysis that accounts for the non-transversality of the grazing contact using the now well-known concept of discontinuity mappings. An example involving both friction and impact shows how the theory may be extended also to the simultaneous presence of other sources of nonsmoothness.

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MS201

Frictional Oscillator Dynamics on Displacement-Dependent Conveyor Systems

This study proposes an analytical method for periodic solutions in frictional oscillators on displacement-dependent conveyor systems. The frictional oscillator is governed by quadratic velocity boundaries, generating two dynamic regimes with contrasting frictional states. Switching criteria containing grazing flow and sliding transition conditions are developed through G-function analysis. Different hybrid mapping structures presenting periodic motions are constructed. Multiple cases will be illustrated to show the mapping structures becoming more complex as the parameters varies, with the emergence of period-2 motions. The framework demonstrates extensibility to broader discontinuous systems with displacement-dependent boundaries

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MS201

Random Maps to Investigate Transition Probabilities and Long-Term Behavior of Energy Harvester

In this talk a stochastic map-based calculation of the vibro-impact energy harvesting system with random restitution coefficient r is presented. This approach is used to track the regular behavior where random r results in a long-time bimodal distribution peaked around the impact velocities in 1:1 dynamics, favorable to energy harvesting. The method based on stochastic maps is valuable not only as a semi-analytical approach for capturing parametric influence on transition probabilities and long-term behavior of the impact dynamics, but also as a method which is computationally efficient relative to full Monte Carlo simulations.

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MS201

Analytical Periodic Motions to Chaos for a Duffing Oscillator with Two Displacement Boundaries

In this talk, the analytical dynamics of a Duffing oscillator (DO) impacting with two symmetric displacement boundaries is discussed. The analytical conditions for the grazing and stuck motions at the two symmetric displacement boundaries are developed. With the discretization of a nonlinear dynamical system, the implicit mapping is used to determine the solution of a DO. The mapping structures for period-m motions with impact chatters are introduced for impact periodic motions of the DO. The bifurcation trees of switching velocities and phases varying with excitation frequency are obtained analytically for a periodically forced DO, and the corresponding stability analysis of impact periodic motions are carried out. The symmetric and asymmetric saddle-node and period-doubling bifurcations are determined, and the motion switching based on the grazing bifurcations is discussed. For a better understanding of the impact dynamics of the DO, numerical illustrations of periodic symmetric and asymmetric motions with impacts are presented. Periodic symmetric and asymmetric motions with grazing are also presented. This study can help one further understand impact behaviors of nonlinear dynamical systems. The method presented in this paper can give the stable and unstable impact periodic motions in nonlinear dynamical systems with impacts. However, in numerical study, the unstable impact periodic motions to chaos cannot be obtained.

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MS203

Fixed Budget Simulation Method for Growing Cell Populations

Investigating the dynamics of growing cell populations is crucial for unraveling key biological mechanisms in living organisms. Classical agent-based simulation algorithms are often inefficient for these systems because they track each individual cell, making them impractical for fast (or even exponentially) growing cell populations. To address this issue, we introduce a novel stochastic simulation approach based on a Feynman-Kac-like representation of the population dynamics. This method maintains a fixed number of Monte-Carlo samples for simulating the system, ensuring a constant computational complexity regardless of the population size. Furthermore, we will also present a series of theoretical results showing the accuracy and reliability of the proposed method. Finally, several biologically relevant numerical examples will be presented to illustrate the approach. Overall, the proposed fixed-budget simulation algorithm effectively addresses the challenge of simulating growing cell populations, providing a solid foundation for better analysis of these systems.

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MS203

Identifiability of SDEs for Reaction Networks

Biochemical reaction networks are widely used across fields, typically analyzed using one of three mathematical frameworks. In this talk, we focus on the diffusion approximation of networks with mass-action kinetics and explore the identifiability of the generator of the associated stochastic differential equations. We provide theorems and practical algorithms for assessing identifiability in different cases. Notably, we demonstrate that some networks have unidentifiable reaction rates, even with full knowledge of the stochastic process, and that distinct networks can generate the same diffusion law under specific conditions. Finally, we compare our results with those from deterministic models and Markov chain frameworks.

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MS203

Network Translation of a Stochastic Reaction Network to Reveal Stationary Distributions

A stationary distribution of a stochastic reaction network describes its long-term dynamics. An analytic formula for a stationary distribution can be obtained for only limited cases, such as linear or finite-state systems. Interestingly, analytic solutions can be easily obtained when underlying networks have special topologies, called weak reversibility (WR) and zero deficiency (ZD). However, such desired topological conditions do not hold for the majority of cases. Thus, we propose a method of translating networks to have WR and ZD while preserving the original dynamics. Additionally, we prove necessary conditions for having WR and ZD after translation. Our method provides a valuable tool for analyzing and understanding the long-term behavior of biochemical systems, and we demonstrate its efficacy with several examples.

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MS203

Classification of 1 Species Stochastic Reaction Networks with Rational Kinetic Functions Based on their Dynamical Features

Continuous-time Markov chains on non-negative integers with multiple jump sizes can be used to model populations with bursty production and decay. Moreover, higher-dimensional reaction networks governed by mass-action kinetics can often be approximated by one-dimensional reaction networks with general kinetic functions under appropriate conditions, such as quasi-steady-state approximations (QSSA) and model reductions. In this talk, we provide criteria for the dynamical features of one-dimensional continuous-time Markov chains with general kinetic functions. We then present a complete classification of single-species reaction networks with rational kinetics based on their dynamical properties, including explosivity, recurrence, positive recurrence, and exponential ergodicity. Our classification relies solely on easily computable quantities: the maximal degree of the jump rates, the mean drift, and the variance. Finally, we demonstrate applications to Michaelis-Menten kinetics, which are frequently used in biology.

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MS205

Symmetry, Invariant Manifolds and Flow Reversals in Active Nematic Channel Flow

In this work, we use equivariant bifurcation theory to classify a subset of exact solutions or exact coherent structures (ECSs) of the active nematic 2D channel flow into various symmetry classes. We uncover the bifurcation sequence that leads to the formation of (relative) periodic orbits (RPOs) that cycle between a vortex lattice periodic orbit with no net streamwise flow, and an almost uniaxial flow state. We propose a mechanism for spontaneous reversal of flow direction based on intersections of invariant manifolds of the symmetry related copies of such an RPO, and find a family of RPOs which exhibit flow reversals, i.e cycle between the left-flowing and right-flowing uniaxial flow states.

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MS205

Closed-Loop Control of a Microtubule-Kinesin Active Fluid

In living systems, active flows are sculpted through entwined chemomechanical and biochemical processes. Model active fluids assembled from a small subset of reconstituted biomolecular components, lacking these regulatory pathways, often exhibit chaotic flows. While shaping these flows through microfluidic devices or manipulating the frictional environment has been a fruitful method for enacting control, such methods are limited by their inability to respond dynamically to the system's state. Toward gaining a better understanding of non-equilibrium material regulation, we demonstrate the use of external feedback control to steer the spatially averaged speed of a microtubule-based nematic. We achieve time-varying actuation by embedding a light-responsive nematic in a system that applies algorithmically determined light intensity based on real-time flow speed measurements. By systematically varying the controller parameters, we find strong agreement between experimental observations of steady-state speed and temporal fluctuations, full nematohydrodynamic simulations, and a coarse-grained model. Our findings demonstrate that feedback control can precisely and accurately regulate the dynamics of active nematics despite challenges posed by the constituents, such as aging, aggregation, and sample-to-sample variability, paving the way for responsive, life-like materials. DOE DE-SC0022291 (experiment and computation: KN,JB,SG,AA,MFH,ZD,SF), DOE DE-SC0022280 (theory: MMN)

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MS205

Control of Coherent Structures in Living Active Matter

Living Active Matter, such as multicellular tissues in early embryonic development, display complex tissue flows driven by self-organizing patterns of active forces. This talk will discuss our recent work on 1) developing active matter models (PDEs) to predict observed tissue flows, and 2) controlling the attractors and repellers of these flows using control theory and direct manipulation of active forces. We apply our framework to multicellular tissue flows in chick embryos, successfully controlling their multicellular attractors and repellers, consistent with experiments in chemically perturbed living embryos. Relevant references include "Serra et al. Science. Adv. (2023), DOI:10.1126/sciadv.adh8152" and "Sinigaglia et al. Phys. Rev. Lett. (2024), DOI:10.1103/PhysRevLett.132.218302".

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MS206

Opinion Dynamics and Climate Change: Insights from Network Models

To increase population engagement in global issues such as climate change or global warming, understanding the complex dynamics of public opinion, which involves many influencing factors, is crucial for addressing global issues like climate change. Opinion models that incorporate interaction networks of primary elements for opinion formation can offer valuable insights into the complex process of opinion formation and its implications for addressing climate change. An opinion model describes a degree-dependent threshold model to simulate how varying levels of influence and social connectivity affect consensus formation. The model shows how key individuals or groups with significant influence can either foster widespread agreement or lead to fragmentation with multiple competing opinions. Another model illustrates how a minority group's opinion can spread throughout the entire system. While these models do not explicitly consider group structures within society, one study examines community structures to understand how bias on an issue can emerge within these community frameworks. These studies shed light on how hierarchical interaction patterns and homophilic community structures can influence opinion shifts on interaction structures. Such insights are particularly relevant to mobilizing public opinion on global issues like climate change, where overcoming entrenched authority and empowering small groups with transformative ideas may be critical to driving societal change.

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MS206

From Opinions to Outcomes: Modeling Climate Change Impact through Discrete and Continuous Perspectives

Climate and humans form a single, complex system in which humans impact the climate and respond to its feedback. Coupled socio-climate mathematical models are essential for understanding the mutual feedback between social and climate systems. Traditional climate models primarily project future emissions and temperature trajectories, overlooking this feedback. However, socio-climate models provide critical insights into how this feedback can alter future climate scenarios compared to models considering natural system processes only. We explore how opinions in a social network influence the climate system and how a changing climate shapes individual opinions. Individual opinions can be discrete or continuous, though most socio-climate models focus on discrete opinions. One study examined how discrete opinions on climate-related rumors and temperature changes affect public attitudes toward mitigation by coupling a rumor propagation model to an Earth System Model. However, in reality, opinions may not be strictly discrete; individuals may have a range of views that reflect varying degrees of commitment to action. To address this, we modified a classic FriedkinJohnsen (FJ) model by coupling it with an Earth System model to understand how continuous opinions on climate change influence future climate scenarios. Our findings suggest that social learning plays a crucial role in shaping future temperature scenarios in discrete and continuous opinions.

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MS207

Evolving Food Web Models Elucidate Directional Invasion of Lineages

Understanding the drivers of species invasion is essential for grasping ecological and evolutionary processes in connected ocean systems. The opening of the Bering Strait around 3.5 million years ago enabled the exchange of species between the Pacific and Arctic Oceans. Evidence shows significant species invasions from the Pacific to the Arctic, while invasions from the Arctic to the Pacific are notably rare. Several hypotheses seek to explain this asymmetry: (1) the Pacific may have had larger population sizes than the Arctic providing greater opportunity for invasion; (2) the Pacific may have supported more diverse populations with traits that facilitate invasion; (3) low diversity in Arctic biota may have led to exploitable empty niches; and (4) species from the Pacific may have reproductive, competitive, or defensive traits that outcompete Arctic natives. In this study, we perform computational simulations using dual eco-evolutionary food web models that allow for species mutations and transfers between webs with invasion success determined by dynamic ecological interactions. We examine the effects of ecological factors (such as resource availability, environmental richness, predation, and competition) and evolutionary factors (including mutation likelihood and strength of trait inheritance) on the likelihood of successful invasions. Our findings attempt to elucidate the ecological and evolutionary parameters that drive asymmetrical invasion patterns.

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MS207

Constant-Selection Evolutionary Dynamics on Multilayer Networks

Multilayer networks have been a useful tool for analyzing population dynamics because they can express the situation in which the individuals in a population are pairwise connected by different types of edges. We explore constant-selection evolutionary dynamics on multilayer networks by extending the Bd process on networks. We use two-layer networks and semianalytically calculate the fixation probability of mutants for each network layer for two-layer networks with high symmetry. Using martingale techniques, we theoretically prove that the complete graph layer and the cycle graph layer in a two-layer network are suppressors of selection, and that the star graph layer and the complete bipartite layer in a two-layer network are more suppressing than the corresponding one-layer network. We then numerically examined our model on four model and empirical two-layer networks. We find that all the two-layer networks that we investigated are suppressors of selection, except for the coupled star networks. However, the coupled star networks are more suppressing than the one-layer star graphs. We conclude that two-layer networks suppress the effects of selection. Our results are surprising because various research since 2005 revealed that most conventional networks are amplifiers of selection under the Bd process. We show amplifiers are not as common as they have been considered once we consider some realistic features of networks.

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MS207

Learning Zero-Determinant Strategies from Scratch

In 2012, a curious class of "zero-determinant" strategies was discovered by William Press and Freeman Dyson. These strategies allow for extensive unilateral control over the outcomes of a repeated game, even allowing for coercive behaviors like extortion in social dilemmas. In the years since, there has been an abundance of research on this class of strategies in various contexts. One common limitation, however, is that these strategies can be difficult to solve for or devise explicitly. I will discuss a different perspective on zero-determinant strategies, showing how one can learn them from scratch (either exactly or approximately) using techniques from reinforcement learning. This allows an agent to one-sidedly align incentives with a greedy opponent, which can be used to mitigate the conflicts of interest commonly found in social dilemmas.

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MS207

Inferring Dynamics With An Evolutionary Symbolic Regression Algorithm

Symbolic regression (SR) is a family of machine-learning techniques for inferring general functions from data. A search process generates algebraic expressions. An optimization process steers the search toward expressions with low prediction error that may yield insights into an underlying physical process. It can discover equations of motion from measurements. This project focuses on a new evolutionary SR algorithm called Jessamine. Each genome consists of instructions applied to input variables, scratch variables, scalar parameters, and output variables. It specifies a function from a state array at one time step to its value at the next. Ridge regression applied to the outputs from the final time step yields a prediction. An optimization routine adjusts the parameters to minimize the prediction error. A selection-mutation process modifies a population of genomes favoring those that yield good predictions. The end result is an interpretable algebraic expression for computing the prediction. The Brusselator reaction-diffusion system is used as a test case. If numerically inaccurate points are filtered out of the training data, the Jessamine system finds expressions for the time derivatives of the concentrations of the two species in terms of spatial data, thereby recovering the underlying PDEs. A future goal is to apply this technique to data from an actual chemical reaction system.

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MS208

Computer Assisted Discovery of Integrability Via Sparse Identification of Lax Operators

We formulate the automated discovery of integrability in Hamiltonian dynamical systems as a symbolic regression problem. Specifically, we seek to computationally maximize compatibility between the known Hamiltonian of the system and a Lax pair of operators using numerical optimization. Our approach is tested on a variety of systems ranging from nonlinear oscillators to canonical Hamiltonian partial differential equations. We test robustness of the framework against nonintegrable perturbations, and, in all examples, reliably confirm or deny integrability. Moreover, using a thresholded l^0 regularization to promote sparsity, we recover expected and discover new Lax pairs despite wide hypotheses on the operators. We will discuss future directions for adapting our framework toward building an all purpose data-driven nonintegrability filter of complex systems.

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MS208

The Fermi-Pasta-Ulam-Tsingou Problem and Nearby Integrable Systems

The famous Fermi-Pasta-Ulam-Tsingou (FPUT) experiment first demonstrated the highly nontrivial process of thermalization in a coupled chain of weakly anharmonic oscillators and subsequently led to a revolution in our understanding of nonlinear science. For the specific energies originally considered, the FPUT lattice is well approximated by several completely integrable equations including the Toda lattice. In this talk we track the evolution of a FPUT chain in the isospectral coordinates of the Toda lattice and show that the two systems sharply diverge at the computed shock-time of a generalized Burgers equation, well before the FPUT lattice reaches equipartition.

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MS208

Traveling Waves of the Burgers' Equation with a Fourth-Order Viscosity

In this talk, we explore the traveling wave solutions of the Burgers' equation with a fourth-order viscosity. We begin with a review of the existence of the solutions. Building on this foundation, we examine stability analyses that further elucidate the long-time behavior of the solutions. Additionally, we introduce related problems concerning traveling wave solutions in the context of fourth-order nonlinear conservation laws.

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MS208

Multi-Modal Solitary Wave Solutions to a Fourth-Order Nonlinear Schrodinger Equation

In this talk, we consider the existence and spectral stability of multi-modal solitary wave solutions to a nonlinear Schrdinger equation incorporating both fourth and second-order dispersion terms. In the bright soliton regime, we show that we can construct multi-modal solitary waves by "gluing together" consecutive copies of the primary solitary wave, as long as certain geometric constraints are satisfied. Under additional assumptions, which can be verified numerically, we prove that all such multi-pulses are spectrally unstable. By contrast, numerical results suggest that, in the dark soliton regime, some multi-modal solutions are in fact stable.

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MS209

Impact of Opinion Formation Phenomena in Epidemic Dynamics: Kinetic Modeling on Networks

In this talk, we present a novel approach to take into account the interplay between infectious disease dynamics and socially-structured opinion dynamics. After the recent COVID-19 outbreaks, it became increasingly evident that individuals' thoughts and beliefs can have a strong impact on disease transmission. It becomes therefore important to understand how information and opinions on protective measures evolve during epidemics. Our work extends a conventional compartmental framework including behavioral attitudes in shaping public opinion and promoting the adoption of protective measures under the influence of different degrees of connectivity. The proposed approach is capable to reproduce the emergence of epidemic waves, specifically providing a clear link between the social influence of highly connected individuals and the epidemic dynamics. Through a heterogeneity of numerical tests we show how this comprehensive framework offers a more nuanced understanding of epidemic dynamics in the context of modern information dissemination and social behavior.

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MS209

Modelling Formation of Echo Chambers from Epistemic Bubbles

Echo Chambers and Epistemic Bubbles "are social structures that systematically exclude sources of information. Both phenomena exaggerate their members confidence in their beliefs, but they operate in entirely different ways and require very different modes of intervention. An epistemic bubble occurs when individuals do not hear from people on the other side of an issue, whereas an echo chamber arises when individuals do not trust people from the opposing side" (C. Thi Nguyen). In this talk, I will present a new model describing the emergence of echo chambers from epistemic bubbles. The model considers three different types of interaction: consensus within a network of direct connections (social network), alignment with news due to homophily (social media), and repulsion from news due to heterophobia (social media). Using this model, I will also introduce a new concept called the 'isolation function', which measures the evolution of dynamics from an epistemic bubble to an echo chamber.

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MS209

An Asymptotic Analysis of Spike Self-Replication and Spike Nucleation of Reaction-Diffusion Patterns on Growing 1-D Domains

Pattern formation on growing domains is one of the key issues in developmental biology, where domain growth has been shown to generate robust patterns under Turing instability. In this work, we investigate the mechanisms responsible for generating new spikes on a growing domain within the semi-strong interaction regime, focusing on three classical reaction-diffusion models: the Schnakenberg, Brusselator, and Gierer-Meinhardt (GM) systems. Our analysis identifies two distinct mechanisms of spike generation as the domain length increases. The first mechanism is spike self-replication, in which individual spikes split into two, effectively doubling the number of spikes. The second mechanism is spike nucleation, where new spikes emerge from a quiescent background via a saddle-node bifurcation of spike equilibria. Critical stability thresholdsfor these processes are derived, and global bifurcation diagrams are computed using the bifurcation software pde2path. These results yield a phase diagram in parameter space, outlining the distinct dynamical behaviors that can occur.

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MS209

Mean-Field Limiting Schemes of a Two-Species Particle Model

We investigate an interacting two-species particle model consisting of leaders and followers. A control acting as a forcing term drives each of the leaders to a desired exit, while at the same time they try to stay close to the center of mass of the followers. We analyze the mean-field limit of this system in two ways: first as the number of followers tends to infinity, and second as the number of leaders also tends to infinity. Numerical simulations are employed to supplement our analysis. This is a joint work with Young-Pil Choi, Giacomo Albi, and Matteo Piu.

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MS210

Learning Iterated Function Systems From Data

Our goal is to create new data-driven modelling techniques for model discovery which can be applied to time series data from random dynamical systems (RDS). We focus on a special class of RDS called iterated function systems, where the noise driving the system can be modelled as a finite state Markov chain. We consider both fully observed and partially observed systems. We identify certain conditions for which the task can be transformed to a multi-manifold clustering problem. Using local manifold learning methods, we can identify different functions in the system. This enables us to recover the Markov chain which generated the data and estimate different properties of the system.

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MS210

Continuation Methods for Point Clouds Which

Represent Smooth Manifolds

Point clouds which represent a smooth manifold arise in the study of nonlinear dynamics as observations of a system. They may represent attractors, or bifurcation diagrams, or simply the image of a smooth set of initial conditions under a flow. This talk will discuss what it means for a point cloud to represent a manifold and how continuation methods can be used to compute these manifolds. Existing Manifold Learning techniques (LLE, ISOMap) are of this type, using one chart per point. This new approach allows for more complicated local approximations derived from many points, for example that are distributed near the manifold. Examples will be presented of a bifurcation diagram of an oscillator, and several invariant tori.

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MS210

Data-Efficient Kernel Methods for Identifying Pdes and Forecasting Dynamical Systems

In many computational science and engineering problems, observational data is available, but the underlying physical models remain unknown. PDE discovery methods provide systematic frameworks to infer these models directly from data. We introduce a unified approach for discovering and solving PDEs using kernel methods. Specifically, given observations of PDE solutions and source terms, our kernel-based, data-driven method learns the functional form of the governing equations. Through numerical experiments, we demonstrate the effectiveness of our method on a variety of interesting PDEs. Additionally, we extend this approach to forecast dynamical systems, particularly Hamiltonian dynamics, from data. We show that our method is especially effective in data-scarce regimes, where only limited observations are available, for both PDE discovery and forecasting Hamiltonian dynamics, and compare its performance to existing methods. We also provide convergence guarantees and a priori error estimates for this methodology.

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MS210

Learning Dynamics of Hidden Variables in Multiscale Viscoelastic Materials

The simulation of multiscale materials poses a significant challenge in computational materials science, requiring expensive numerical solvers that can resolve dynamics of material deformations at the microscopic scale. The theory of homogenization offers an alternative approach to modeling, by locally averaging the strains and stresses of multiscale materials and hence eliminating their smaller scales. Localaveraging introduces history dependence between the dynamics of average strain and average stress of a material which can be described by the mathematics of Volterra integral equations. First, we delve into an interesting and old mathematical problem of deconvolution or inversion of Volterra integral equations, a problem which was actively studied but not fully resolved in the materials science and mathematics communities. We present novel and general analytic solutions for the inversion of Volterra equations of the first, second, and integro-differential type and show that this gives a closed-form solution for the dynamics of a large class of one dimensional viscoelastic materials. Driven by this closed-form theory, we develop a data-driven neural network model that, across a wide range of multiscale materials, accurately predicts their dynamics, thus enabling us to simulate their deformations under forcing. We use the approximation theory of neural operators to provide guarantees on the generalization of our approach.

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MS211

Threshold Dynamics in a Time-delayed Periodic Model for Measles Spread with Passive Immunity and Double-dose vVaccination

We present a compartmental model for measles transmission, considering passive immunity of newborns due to maternal antibodies, a double-dose vaccination routine and a partial and waning immunity of those who only received one dose of vaccine. The latent period of the disease appears in the form of a time delay. We determine the basic reproduction number and prove that it serves as a threshold parameter regarding the global dynamics of the system and disease persistence. We apply the model to 2014–17 data from India, one of the countries mostly affected by measles. The model provides a good fit to epidemiological data. We apply sensitivity analysis to determine the parameters with the strongest influence on epidemic spread and perform numerical simulations to assess the effects of changing these parameters. Joint work with Jayanta Mondal, Piu Samui and Mahmoud A. Ibrahim.

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MS211

Delay Equations in HIV Dynamics Models

Time delays in the progression of HIV infection, representing biological processes such as the onset of viral production and the adaptive immune response, play an important role in understanding HIV dynamics. In this talk, I will present a few models that incorporate distinct delays related to latency and immune response activation. We start with a model that includes delays for viral production post-infection and the emergence of the immune response, which aligns more closely with patient data, as demonstrated by comparisons with viral load data from HIV-infected individuals. We also analyze a model focusing on delays in latency establishment and subsequent viral production, examining how these delays impact the stability of infection states. By exploring stability conditions, Lyapunov functionals, and stability crossing curves, we demonstrate the significant influence of time delays on infection dynamics.

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MS211

Evolution of the Maturation Period in Insect Populations

We propose a new mathematical model to address the evolution of maturation period, building on the Nicholson's blowfly equation. First a competition model of two species is formulated as a system of nonlinear delay differential equations with two distinct delays, and we analyze its dynamics. Then we consider the evolutionary dynamics of maturation periods. For some cases, we identify the optimal maturation delay for an insect population, depending on the quality and suitability of the habitat, which is both a globally evolutionary stable and convergence stable strategy. We investigate the potential co-existence of insects with different maturation delays. Mathematically interesting questions raised by the invasibility of oscillatory insect populations. Joint work with Xingfu Zou.

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MS212

Deciphering Alzheimers Disease Dynamics: Insights into Protein Pathology, Clearance, and Therapeutic Strategies

By 2030, an estimated 78 million people will be living with Alzheimer's disease (AD). Despite extensive research, AD clinical trials face a staggering 98% failure rate, underscoring the urgent need for a deeper understanding of drug and disease dynamics and robust in silico models. Mathematical modelling has joined the fight against AD and allows for safe, ethical, and cost-effective in-silico experimentation in man. My research delivers the first network reaction-diffusion system that integrates clearance, aggregation, and drug actions at the spatial and temporal scales of the disease, offering novel insights into potential treatments. Neurodegenerative diseases, such as AD, are marked by the assembly of toxic proteins into oligomers and fibrillar aggregates that spread across the brain, initiating protein aggregation in neighbouring regions. This autocatalytic progression depends on multiple factors that could be targeted therapeutically. In this talk, I will describe how we capture these dynamics by employing spatially extended nucleation-aggregation-fragmentation models for prion-like protein spreading and interactions within the brain, focusing on the impact of different drugs on AD progression. Our analytical insights and computational results, on high-resolution human brain graphs, reveal crucial connections between clearance mechanisms and neurodegeneration, optimal dosing regimens, and a critical window in which the disease must be caught.

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MS212

The Dynamics of Sleep-wake Regulation: Towards Digital Twins for Sleep Timing Disorders

Sleep is often disrupted in neurological disorders. There is evidence that the relationship is bi-directional so that neurological disorders result in sleep disruption and sleep disruption leads to worsening of symptoms driving a downward spiral in conditions such as depression. Late sleep timing can be a particular problem. In delayed sleep-wake phase disorder people spend much of the night awake, eventually falling asleep in the early hours of the morning. They then experience profound difficulty waking up in time for school, work or social commitments. If they manage to get up in time, sleepiness, fatigue, mood and cognitive difficulties typically result. Non-smooth coupled oscillator models that capture the essence of the underlying physiology (circadian rhythmicity and sleep homeostasis) and key environmental factors (light exposure) have been developed. In this talk I will discuss some of our recent work that uses our most recent modelling advances to quantitatively describe individual sleep timing. Using data collected from those living with schizophrenia, Ill illustrate how seasonal desynchrony with the 24 h day, can be explained. Ill also discuss how we are combining models and data to develop digital twins for sleep-wake regulation, with the aim of creating personalised guidance to ameliorate delayed sleep timing phase disorders.

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MS212

Modelling Cross-Species Neural Dynamics in Genetic Risk of Schizophrenia

Schizophrenia is a chronic mental disorder affecting 20 million people globally, with symptoms including psychosis, delusions, and disorganised thinking. A key symptom is distorted perception, such as auditory and visual hallucinations. Treatments primarily target symptoms and not the underlying disorder, and are often ineffective, highlighting the need to better understand the mechanisms of schizophrenia. In recent years major advancements in our understanding of the genetics of schizophrenia have been made through large-scale consortia associating a number of rare Copy Number Variants (CNVs) - deletions or duplications of sections of DNA - with increased risk of schizophrenia. To understand how these CNVs alter the dynamics of the brain and lead to schizophrenia-like symptoms such as perceptual distortion, we measured neural responses to sensory stimuli using brain imaging data from affected children (MEG and MRI) and rodents (EEG). Features of altered dynamics were characterised using a projection-based approach which we have shown performs comparably to traditional source localisation but gives theoretically optimal signal-to-noise ratio and no need to a-priori select sources. Subsequently, we developed a novel multi-scaled neural mass model of early sensory systems with biophysically meaningful parameters and realistic thalamocortical architecture and used Bayesian optimisation (dynamic causal modelling) to explore the underlying synaptic and neuronal mechanisms.

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MS213

Disorder-Induced Cyclops States in Kuramoto Networks with Higher-Mode Coupling

Cyclops states are intriguing cluster patterns observed in oscillator networks, including neuronal ensembles. The concept of cyclops states formed by two distinct, coherent clusters and a solitary oscillator was introduced in [Munyaev *et al.*, Phys. Rev. Lett. 130, 107021 (2023)], where we explored the surprising prevalence of such states in repulsive Kuramoto networks of rotators with higher-mode harmonics in the coupling. This talk extends our analysis and reveals the mechanisms responsible for stabilizing unstable cyclops states in networks of identical Kuramoto oscillators with inertia and higher-mode coupling via intrinsic frequency detuning.

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MS213

Disorder-Promoted Network Dynamics

Recent research has shown that heterogeneity can facilitate synchronizationa finding that defies conventional expectations. In this talk, we extend this line of inquiry to demonstrate that heterogeneity can be harnessed not just for synchronization but to promote a broader range of collective dynamics within network systems. By examining both theoretical models and empirical evidence, we reveal how the controlled introduction of disorder can lead to emergent dynamics that align with specific, desirable network behaviors. The talk concludes by discussing selected applications and implications across diverse domains.

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MS213

Dynamics of Oscillator Populations with Random Interactions

We consider large populations of phase oscillators with maximal heterogeneity in interactions - all coupling functions are taken randomly from some distribution. We show that upon a reasonable assumption of independence of the interactions and the phases, one can transform the dynamics to an effective homogeneous ensemble with averaged coupling functions. Examples include cases where the randomness enters the coupling strengths and the phase shifts. Furthermore, we analyze the situation with full frustration due to a uniform distribution of the phase shifts in the coupling. Here a subtle transition to partial synchrony is observed, description of which requires introduction of a novel correlation order parameter.

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MS213

Disorder in Aid of Order

I will review results from my research group demonstrating how a collection of chaotic systems can be tamed by random coupling connections, heterogeneity in the constituent chaotic sub-systems and asynchronicity in dynamical evolution, i.e. disorder and asymmetry can induce ordered behaviour. The phenomena will be discussed in the context of a wide class of systems, ranging from coupled oscillators to biochemical, neural and infection spreading networks. We will also show how dynamically switched random links can prevent blow-ups in coupled nonlinear systems suffering from unbounded growth. Lastly we will demonstrate that random connections can destroy chimeras, yielding more homogeneous and ordered states.

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MS214

Modelling the Coarse-Grained Dynamics of Particles with Ligand-Receptor Contacts

One way to glue objects together at the nanoscale or microscale is by ligand-receptor interactions, where short sticky hair-like ligands stick to receptors on another surface, much like velcro on the nanoscale. Such interactions are common in biological systems, such as white blood cells, virus particles, cargo in the nuclear pore complex, etc, and they are also useful in materials science, where coating colloids with single-stranded DNA creates particles with programmable interactions. In these systems, the ligand-receptor interactions not only hold particles together, but also influence their dynamics. How do such particles move? Do they roll on each others surfaces, as is commonly thought? Or could they slide? And does it matter? In this talk I will introduce our modelling and experimental efforts aimed at understanding the coarse-grained dynamics of particles with ligand-receptor interactions. Our models predict these interactions can change the particles' effective diffusion by orders of magnitude. Our experiments, using DNA-coated colloids, verify this dramatic dynamical slowdown, but also show the particles undergo subdiffusion at many temperatures, an observation we dont yet understand.

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MS214

Anomalous Processes Emerging from Large Deviation Estimators

The problem of estimating large deviations of a time-averaged observable arises in many contexts, including estimating free energy differences (Jarzynski estimator), determining buffer sizes in ATM networks, and predicting population growth from single-cell dynamics. Estimating large deviations rate functions requires an exponentially large amount of data, since the events of interest are exponentially rare. Consequently, it is natural to study the behavior of large deviation estimators in the limit where the sample size grows exponentially with the large deviation parameter. In this talk I will present some results about the limit behavior of large deviation estimators and the approximation of their sample distribution by anomalous processes. I will also discuss the connection between these sampling problems and models in disordered systems, specifically the random energy models

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MS214

A Mean First Passage Time Theory for Velocity Jump Processes

Velocity jump processes describe particle trajectories that are piecewise ballistic with changes in velocity occurring at exponentially distributed time intervals and with new velocities drawn from a given kernel. This class of processes encompasses classical diffusion while also significantly generalizing it by describing particle motion through two quantities; the interval between jumps and the distribution of velocities. For the first time, we derive a Mean First Passage Time (MFPT) theory for this class of stochastic processes. Our derivation leads to a new integro-PDE for the MFPT whose solution yields the average time for a particle to reach an absorbing state from a given initial configuration. In this talk, we will discuss the details of the derivation, demonstrate the resulting theory in radially symmetric geometries and finally apply the new result to data from ecological examples.

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MS214

Modulation Equations for the Space Fractional Swift-Hohenberg Equation

The Swift-Hohenberg equation is a basic model motivated by pattern formation in fluid dynamics. In this talk, we consider a space fractional version of this equation where the Laplace operator is replaced by the (non-local) fractional Laplacian. We study the dynamics of this model near instability relying on amplitude/modulation equations. More precisely, we prove that the fractional Swift-Hohenberg model can be approximated by a Ginzburg-Landau equation.

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MS215

Life in Complex Environments

How does the swimming motion of bacteria affect the mixing of passive scalars in chaotic flows? Answers to this question can lead to a better understanding of the formation of algal blooms in oceans and lakes, as well as potentially useful applications in vaccine and biofuel production. In this talk, I will show that the coupling between flow structure and swimmer motion can lead to unexpected phenomena including bacterial trapping, adverse large-scale scalar transport, and manifold trafficking. In particular, experiments and simulations show that the flow Lagrangian Coherent Structures (LCS) are intimately connected to the fate of bacteria and scalar mixing in time-periodic flows (see Figure). For example, it has recently found that the presence of bacteria hinders passive scalar large-scale transport and reduces overall mixing rate in a 2D chaotic flow. Stretching fields, calculated from experimentally measured velocity fields, show that bacterial activity attenuates fluid stretching and lowers flow chaoticity. Simulations suggest that this attenuation may be attributed to a transient accumulation of bacteria along regions of high stretching, or unstable manifolds. On the other hand, at small scales, activity seems to enhance local mixing. Overall, our results show that once can design flows with specific structures and dynamical features to control the trapping and dispersion of bacteria, as well as enhance scalar mixing.

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MS215

It Goes Both Ways: Exploring How Chemotaxis Shapes Reciprocal Marine Microbial Interactions

Chemical cues dominate marine microbial interactions, ultimately dictating ecosystem-scale processes such as carbon fixation and nutrient recycling. A key primary producer are the marine picocyanobacteria *Synechococcus* and *Prochlorococcus*, contributing a quarter of global oceanic primary production. Recent experimental work has shown that, at the bulk scale, chemotaxis enhances reciprocal exchange in cyanobacteria-bacteria interactions, contrasting with previous assumptions that the chemical environment surrounding cyanobacteria (the “phycosphere’) was too small to influence neighbouring microbes. Here we combine microfluidics, microscopy, metabolomics, and spectroscopy to probe directly single-cell motility-driven interactions. Using microfluidics and time-resolved metabolomics, we show that viral infection drastically enhances chemotaxis between *Synechococcus* and heterotrophic bacteria, significantly increasing encounters and subsequently access to dissolved material for bacteria. Combining Raman spectroscopy with hydrogel microfluidics, we establish the first direct experimental measurements of distance-dependent uptake of isotope-labelled carbon from individual bacteria to *Synechococcus*, proposing the concept of a “bacteriosphere’. Taken together, our work explores the reciprocal nature of key motility-driven microbial interactions, with direct implications for our understanding of global nutrient and material fluxes.

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MS215

Boundary Conditions for Active Brownian Particles

We consider the transport of active particles inside a channel domain. These are treated using the Active Brownian Particle model (ABP), where particles move forward at constant speed but in a randomly-varying direction. We examine their accumulation near the boundary as the singular limit of a better-behaved model that includes small spatial diffusion. We present matched asymptotic approximations that describe their reduced dynamics at long times. In the reduced dynamics, the probability density for the particle position has a singular component localised on the boundary which is coupled in two-way fashion to the smooth interior component. The results are illustrated by a number of numerical simulations.

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MS215

Orientational Dynamics of Microorganisms in Fluid Flow

Microbial swimming is usually modeled by straight runs followed by random, discrete tumbling events with extra stochasticity. We offer a different perspective. Instead of discrete random tumbling events, we model the angular dynamics as a continuous process: Lévy flights in orientation. We analyze experimental trajectory data from wild-type *Bacilus subtilis*, a smooth swimming variant of *Bacilus subtilis*, *Tetraselmis suecica*, and *Euglena gracilis* and show the angular statistics either closely resemble either a Lorentzian distribution, or a Voigt profile (the convolution of a Gaussian and Lorentzian). We offer a course grained model for the time evolution of the probability distribution. Each individual microbe trajectory has different deterministic behavior, such as helices of different sizes and frequencies and circular arcs with different radii. We analyze the random nature of the deterministic behavior in the ensembles and offer an ensemble theory for random drift terms. This ensemble theory explains many of the qualitative features in the data that cannot be explained by a pure noise model. From this theory we estimate the strength of Lorentzian noise for the different populations of microbes, and show that Gaussian noise is not the dominant process causing the angular statistics to follow a Voigt profile. Thus we may think of microbial run and tumble dynamics as a single continuous stochastic process.

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MS216

Adaptive Meshing for Ensemble Based Data Assimilation

Adaptive spatial meshing has proven invaluable for the accurate, efficient computation of solutions of time dependent partial differential equations. In a DA context the use of adaptive spatial meshes addresses several factors that place increased demands on meshing; these include the location and relative importance of observations and the use of ensemble solutions. To increase the efficiency of adaptive meshes for data assimilation, robust look ahead meshes are developed that fix the same adaptive mesh for each ensemble member for the entire time interval of the forecasts and incorporate the observations at the next analysis time. This allows for increased vectorization of the ensemble forecasts while minimizing interpolation of solutions between different meshes. The techniques to determine these robust meshes are based upon combining metric tensors or mesh density functions to define non-uniform meshes. We illustrate the robust ensemble look ahead meshes using traveling wave solutions of a bistable reaction-diffusion equation. A numerical experiment with different observation scenarios is presented for a coupled system of two 1D Kuramoto-Sivashinsky equations,.

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MS216

Domain and Spectral Localization for Square Root Filters

Localization is a key part of many Data Assimilation (DA) schemes. For problems with complex behavior, localization is employed to reduce spurious correlations, reduce the complexity of the calculations, and subsequently improve the numerical results. Ensemble Kalman Filter techniques have seen various methods of localization used.We focus on so-called square root filters, which form analysis updates as linear combinations of ensemble forecast anomalies. This talk will discuss how to formulate localizations of these filters using model and data space projections. We investigate different choices within this framework. We will see how domain and spectral localization are implemented under this paradigm and illustrate the utility of the methods with numerical experiments. Lastly, we discuss possible avenues in which this formulation may be used in the future.

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MS217

Nonlinear Optimal Design with Active Learning Gradient Flow

Identifying valuable measurements is one of the main challenges in computational inverse problems. This is often framed as the optimal experimental design (OED) problem. In this talk, we discuss the OED within a continuously-indexed design space, which is in contrast to the traditional approaches on selecting experiments from a finite measurement set. This formulation better reflects practical scenarios where measurements are taken continuously across spatial or temporal domains. However, optimizing over a continuously-indexed space introduces computational challenges. To address these, we employ gradient flow and optimal transport techniques, implemented via Monte-Carlo particle method. This novel OED algorithm scheme has showed its applicability on various kinds of physical models across fields, from tomography to quantum mechanics to dynamical systems. The design results returned by the proposed gradient flow algorithms capture informative measurements and meanwhile successfully solve the reconstruction task.

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MS217

Continuous Data Assimilation for Hydrodynamic Moment Recovery

Motivated by the challenge of moment recovery in hydrodynamic approximation in kinetic theory, we propose a data-driven approach for hydrodynamic models. Inspired by continuous data assimilation, our method introduces a feedback control nudging system. This approach facilitates the simultaneous recovery of both the unknown force term and a high-resolution solution from sparsely observed data. To address potential numerical artifacts, we use kernel regression to fit the observed data. We also analyze the convergence of the proposed nudging system under both full and partial data scenarios. When applied to moment systems, the source term involves the derivative of higher-order moments, our approach serves as a crucial step for data preparation in machine-learning based moment closure models. The effectiveness of our algorithm is demonstrated through multiple numerical experiments.

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MS217

A Physics-Informed Model for Representing Pulsatile Blood Flow from Ancillary Measurements

Continuous blood pressure monitoring, via a non-invasive wearable: for example, a smart watch, is an elusive problem in in-home medical monitoring. Using a measured bioimpeadance (BioZ) signal, we endeavor to predict the causal blood pressure signal in a patient's radial artery. For this task, we introduce a physics informed neural network autoencoder. Our model assimilates measured BioZ signals with Navier-Stokes informed blood pressure and velocity solutions that stem from standard PINN loss and training techniques. We achieve this by simultaneously training a PINN with augmented feature inputs from a BioZ and relevant patient physiology encoder, to yield physiologically informed and hydrodynamically consistent solutions. Further, we regularize our model's predictions by "decoding" these pressure and velocity signals to reconstruct the original input BioZ signal. Our model produces promising results when trained on a variety of datasets.

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MS218

Closed-Loop Koopman Operator Approximation

This presentation discusses a previously published method to identify a Koopman model of a feedback-controlled system given a known controller. The Koopman operator allows a nonlinear system to be rewritten as an infinite-dimensional linear system by viewing it in terms of an infinite set of lifting functions. A finite-dimensional approximation of the Koopman operator can be identified from data by choosing a finite subset of lifting functions and solving a regression problem in the lifted space. Existing methods are designed to identify open-loop systems. However, it is impractical or impossible to run experiments on some systems, such as unstable systems, in an open-loop fashion. The proposed method leverages the linearity of the Koopman operator, along with knowledge of the controller and the structure of the closed-loop system, to simultaneously identify the closed-loop and plant systems. The advantages of the proposed closed-loop Koopman operator approximation method are demonstrated experimentally using a rotary inverted pendulum system. An open-source software implementation of the proposed method is publicly available, along with the experimental dataset generated for this paper.

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MS218

Koopman Control Family and Universal Finite-Dimensional Forms

We introduce the Koopman Control Family (KCF), a Koopman-based axiomatic framework for representing general (not necessarily control-affine) discrete-time nonlinear control systems. KCF includes all Koopman operators for autonomous (input-free) systems created by setting the control input to a constant value. We demonstrate that KCF can fully characterize the system's behavior over an appropriate function space. Since KCF contains uncountably many operators, its direct implementation is challenging. To address this, we parametrize KCF over the input set and show that its behavior is captured via a single linear operator on an augmented function space. Given the importance of finite-dimensional models in control applications, we introduce a universal finite-dimensional form for KCF, called the "input-state separable" model, using a generalized concept of subspace invariance. Notably, the input-state separable form includes the commonly used Koopman-based linear, bilinear, and switched linear models as special cases. When the subspace is not invariant under KCF, we provide best approximations in input-state separable form. Moreover, we characterize the accuracy of these approximated models via "invariance proximity," which measures worst-case prediction error across all functions in the finite-dimensional space. Finally, we discuss how our framework applies to data-driven modeling. This work is based on the following preprint: https://arxiv.org/abs/2307.15368

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MS218

Koopman Operator, Entity-Based Systems, and Video Game

The Koopman operator does magic: it can be used to represent complex nonlinear dynamics, say those governing a turbulent flow or the computer program that encodes a video game, into a linear dynamical system. The goal of this talk is to provide a tutorial introduction to the Koopman operator, not as a mathematical object, but rather as a practical tool to solve control and decision problems. To this effect we will first discuss how the Koopman operator can do its linearization magic and then how this can help solving control problems. In the talk we discuss two specific optimization approaches, one based on dynamic programming and the other on Markov-Chain Monte Carlo (MCMC) methods. In the last few years, our interest in the Koopman operator has been motivated by optimizations arising in multi-agent systems, for which games of strategy and video arcade games provide interesting and challenging examples. The dynamics of these types of games generally present a special structure (which we refer to as entity-based systems) that helps to develop the Koopman representation. In this talk, we will most use examples that have this type of structure.

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MS218

Koopman-Based Feedback Design with Closed-Loop Guarantees: A Data-Driven Control Approach for Nonlinear Systems

This talk presents recent advancements in data-driven controller design for nonlinear dynamical systems, focusing on ensuring closed-loop stability through Koopman operator theory. The Koopman operator allows to rewrite a nonlinear control-affine system as an infinite-dimensional bilinear system. For a tractable representation, we restrict ourselves to a finite-dimensional bilinear surrogate model that approximates the action of the Koopman operator. By incorporating robust control strategies, we develop state-feedback controllers that rely only on measurement data while explicitly accounting for errors arising from the finite-dimensional approximation. In particular, we discuss the Stability-and-certificate-oriented EDMD (SafEDMD) framework, which provides rigorous stability guarantees through proportional error bounds, enabling a reliable controller design. This method, applicable to both continuous-time and discrete-time systems, results in a nonlinear controller parameterization inspired by gain-scheduling techniques, efficiently solved using semidefinite programming and linear matrix inequalities. Further, we discuss how the SafEDMD controller can be generalized, e.g., by using predictive control. Numerical examples are presented to demonstrate the successful application of the SafEDMD controller and its advantages over existing Koopman-based control methods.

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MS219

Periodic Motions for a Switching System Through Two Nonlinear Duffing Oscillators

In this talk, stable and unstable periodic motions in a switching system consisting of two different Duffing oscillators switched with specific times are presented semi-analytically. A semi-analytical method is adopted through global switching mappings. In specific time intervals, the switching mappings are generated by the sub-implicit mappings of the differential equations of two nonlinear systems. The sub-implicit mappings are obtained through discretization of nonlinear differential equations. To determine periodic motions in the switching systems, the global mapping structures are developed with the corresponding nonlinear algebraic equations of the sub-implicit mappings. The stability and bifurcations of periodic motions in the switching system are determined from the eigenvalue analysis. The bifurcation trees of periodic motions varying with excitation frequency are given with different excitation amplitudes. From the analytical solutions, the initial conditions are chosen for numerical results. The numerical and analytical results in nonlinear switching system based on the two Duffing oscillators are compared. For unstable periodic motions, with simulation time increase, the unstable periodic motions moved away from the analytical solutions. In this paper, a method is presented for how to determine semi-analytical solutions of periodic motions in nonlinear switching systems.

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MS219

Equilibrium Networks and Switching Bifurcations

In this talk, equilibrium networks with two connected hyperbolic and hyperbolic-secant flows are presented, and the corresponding switching bifurcations are discussed. The horizontal and vertical inflection-sink infinite-equilibriums exist for the switching bifurcations. On the infinite-equilibriums, there are the parabola-saddle and inflection-source (sink) bifurcations. Parabola-saddle switching bifurcations are for the hyperbolic flow with paralleled center, hyperbolic-secant flow with paralleled positive and negative saddles. The inflection-source (sink) switching bifurcations are for the hyperbolic flow with connected saddle and the hyperbolic-secant flow with connected source and sink. The double-inflection diagonal saddles are for the double switching bifurcations in the two directions.

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MS219

Discontinuity Mappings for Stochastic Piecewise Smooth Systems

Many recurrent dynamical systems that originates from rigid-body systems are nonsmooth or piecewise-smooth (PWS) in their nature due to interactions with the environment through impacts, friction or control. For a few decades, we have been able to successfully determine the linear stability of periodic orbits of PWS systems with the aid of saltation matrices, which also allows for continuation of periodic orbits and other invariant sets. As a natural extension, we will introduce the concept of a stochastic saltation matrix (SSM) that allows us to get a handle of long-term invariant limit-distributions for systems with stochastically oscillating boundaries or boundaries with stochastic surface profiles. We will describe different scenarios where SSMs can play important roles when estimating long-term behaviours as well as address open questions for PWS systems in general, and stochastic PWS system in particular.

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MS219

Local Stability of Stochastic Limit Cycles of Vibro-Impacting Systems with Soft and Hard Barriers

This work introduces a suite of metrics to quantify the local stability of a continuously perturbed trajectory along periodic orbits. Stability is observed to vary as a function of the volume occupied by a bundle of noisy trajectories around the deterministic limit cycle and its proximity to the basin boundary. The computation method accounts for both local perturbations and the position of basin boundaries within the state space. This approach enables identification of segments along the orbit where the system is more prone to transition between co-existing basins of attraction. To assess the effectiveness of this framework, noise-induced intermittent transitions were numerically computed across nonsmooth dynamical systems with varying degrees of smoothness. For systems with additive or multiplicative colored noise of specific intensity and correlation, the Poincar section obtained at stroboscopic intervals maintains its orientation in state space, affirming that the underlying system dynamics significantly influences the stochastic behavior. This analysis may be extended beyond limit cycles by assigning an asymptotic or approximate phase (isophase) to aperiodic attractors, such as chaotic and quasiperiodic attractors. Drawing on existing literature, this work establishes methods for effective phase quantification of these attractors, facilitating identification of escape regions and the boundaries of noisy basins of attraction.

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MS220

Mean-Field Approximation for Networks with Synchrony-Driven Adaptive Coupling

Synaptic plasticity is a key component of neuronal dynamics, describing the process by which the connections between neurons change in response to experiences. In this study, we extend a network model of θ-neuron oscillators to include a realistic form of adaptive plasticity. In place of the less tractable spike-timing-dependent plasticity, we employ recently validated phase-difference-dependent plasticity rules, which adjust coupling strengths based on the relative phases of θ-neuron oscillators. We investigate two approaches for implementing this plasticity: pairwise coupling strength updates and global coupling strength updates. A mean-field approximation of the system is derived and we investigate its validity through comparison with the θ-neuron simulations across various stability states. The synchrony of the system is examined using the Kuramoto order parameter.

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MS220

A New Generation of Reduction Methods for Networks of Neurons with Complex Dynamic Phenotypes

Collective dynamics of spiking networks of neurons has been of central interest to both computation neuroscience and network science. Over the past years a new generation of neural population models based on exact reductions (ER) of spiking networks have been developed. However, most of these efforts have been limited to networks of neurons with simple dynamics (e.g. the quadratic integrate and fire models). Here, we present an extension of ER to conductance-based networks of two-dimensional Izhikevich neuron models. We employ an adiabatic approximation, which allows us to analytically solve the continuity equation describing the evolution of the state of the neural population and thus to reduce model dimensionality. We validate our results by showing that the reduced mean-field description we derived can qualitatively and quantitatively describe the macroscopic behaviour of populations of two-dimensional QIF neurons with different electrophysiological profiles (regular firing, adapting, resonator and type III excitable). Most notably, we apply this technique to develop an ER for networks of neurons with bursting dynamics.

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MS220

Mean-Field Approximations of Networks of Spiking Neurons with Short-Term Synaptic Plasticity

Recent advances in deriving mean-field descriptions for networks of coupled oscillators have sparked the development of a new generation of neural mass models. Of notable interest are mean-field descriptions of all-to-all coupled quadratic integrate-and-fire (QIF) neurons, which have seen numerous extensions and applications. These extensions include different forms of short-term adaptation which play an important role in generating and sustaining dynamic regimes in the brain. It is an open question, however, whether the incorporation of presynaptic forms of synaptic plasticity driven by single neuron activity would still permit the derivation of mean-field equations using the same method. Here we discuss this problem using an established model of short-term synaptic plasticity at the single neuron level, for which we present two different approaches for the derivation of the mean-field equations. We compare these models with a recently proposed mean-field approximation that assumes stochastic spike timings. In general, the latter fails to accurately reproduce the macroscopic activity in networks of deterministic QIF neurons with distributed parameters. We show that the mean-field models we propose provide a more accurate description of the network dynamics, although they are mathematically more involved. Using bifurcation analysis, we find that QIF networks with presynaptic short-term plasticity can express regimes of periodic bursting activity as well as bistable regimes.

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MS220

Stochastic Neural Mass Model for Beta Bursts and Non-Averaged Neural Data

Classically, neural oscillations were believed to be sustained oscillations that varied in amplitude over time due to certain tasks being performed. However, this picture was formed from trial averaged data. Studies investigating non-averaged data show that *beta oscillations* occur in so-called bursts, which are transient spikes in power in the beta frequency range, rather than sustained oscillations. Both the duration and power of these bursts are increased, and the burst rate is decreased in people with *Parkinsons Disease* (PD) in comparison to healthy controls (Vinding, M. C., et al, 2020). In this work, we employ a *next generation neural mass* model (Byrne, ., et al, 2020) to generate bursting beta activity and study the characteristics of these bursts. By posing the model close to a Hopf bifurcation and driving it with noise, the model produces brief bursts of beta activity, as seen in real non-averaged EEG and MEG data. Next, we perform a thorough parameter investigation to understand how the parameters and their associated mechanisms affect the burst characteristics. Using these findings, we identify parameter manipulations that result in increased beta power, reduced burst rate, and increased burst durations, and as such identify potential mechanisms disrupted in PD. These results may help identify biomarkers of PD, aiding in the assessment and treatment of patients with the disease.

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MS221

Stability of Reaction Networks with Time Changing Parameters

Since the dawn of stochastic chemical reaction network theory over 50 years ago, there have been many general results about (positive) recurrence, especially in the case of mass-action kinetics. One less-explored area is that of mass-action models whose rate constants, rather than being static, are themselves stochastic. Such models have relevance in applications, since biomolecular systems rarely exist in isolation and their rates often depend on time-changing quantities. In this series of two talks, we investigate the positive recurrence of one of the simplest cases of these stochastic rate constants models, with two species, at most monomolecular source complexes, and rate-constants that switch stochastically between two possible sets of options. Already in this special case, it will turn out that the possible overall behaviors are rich. Specifically, in this talk I will introduce the topic and discuss when positive recurrence is achieved in two related settings: the first setting concerns networks with monomolecular complexes whose rates change stochastically over time, based on joint work with Abhishek Pal Majumder and Carsten Wiuf. The second setting concerns models with monomolecular source complexes (but general product complex) and rates randomly switching between two value sets at a low speed, based on joint work with Chuang Xu.

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MS221

Stochastic Analysis of Markov Chain Models for Chromatin Dynamics

It was previously found via simulation that the stochastic dynamics and time-scale di]erences between establishment and erasure processes in chromatin modifications (such as histone modifications and DNA methylation) can have a critical e]ect on maintaining and switching cell types through generations of cell division. Moreover, cross- catalysis between repressive histone modifications and DNA methylation quickly silences a gene, and protein-mediated positive autoregulation can alleviate this silencing. In this talk, we provide a rigorous mathematical framework to validate and extend computational insights. We treat our stochastic models of chromatin modification circuits as singularly perturbed, continuous-time Markov chains with a small parameter ε capturing the time scale separation. We characterize the limiting stationary distribution as ε goes to zero in terms of a reduced Markov chain. We also show that protein- mediated positive autoregulation can monotonically alleviate cross-catalytic silencing caused by two types of repressive modifications. The theoretical tools developed not only provide a solid mathematical foundation for our previous computational findings, emphasizing the role of chromatin modification dynamics and protein-mediated autoregulation, but also have broader applications to singularly perturbed continuous time Markov chains, particularly those associated with chemical reaction networks.

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MS221

Robust Adaptation in Stochastic Chemical Reaction Systems

Robust Perfect Adaptation (RPA) is a crucial self-regulatory mechanism where a system maintains steady-state output values despite environmental perturbations without fine-tuning system parameters.While RPA has been extensively studied in deterministic chemical reaction networks, its behavior in stochastic systemswhich better reflect real-world molecular interactionsremains less understood. We previously developed a topological framework that comprehensively characterizes RPA properties in deterministic chemical reaction systems based on network topology. In this talk, we present a novel extension of this approach to stochastic reaction networks, revealing how network topology constrains and enables robust adaptation under molecular noise.

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MS221

Stability of Reaction Networks with Randomly Switching Parameters. Part II: Transience

Since the dawn of stochastic chemical reaction network theory over 50 years ago, there have been many general results about (positive) recurrence, especially in the case of mass-action kinetics. One less-explored area is that of mass-action models whose rate constants, rather than being static, are themselves stochastic. Such models have relevance in applications, since biomolecular systems rarely exist in isolation and their rates often depend on time-changing quantities. In this series of two talks, we investigate the positive recurrence of one of the simplest cases of these stochastic rate constants models, with two species, at most monomolecular source complexes, and rate-constants that switch stochastically between two possible sets of options. Already in this special case, it will turn out that the possible overall behaviors are rich. Specifically, this second talk will present a Hurwitz-matrix-type sufficient condition for a parameter-switching model to be transient even when the two individual networks that it switches between are positive recurrent, provided that the switching rate is fast enough. We will discuss some of the high-level ideas behind the proof, which will hopefully be applicable for proving transience in other settings. This talk is based on joint work with Daniele Cappelletti and Chuang Xu.

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MS223

Learning a Hydrodynamic Model of Active Nematics with Physics-Informed Sparse Regression

Library-based sparse regression has cemented itself as a uniquely effective tool for equation discovery. Sparse regression quickly determines quantitatively accurate and qualitatively simple equations directly from numerical or experimental data. The model discovery paradigm Sparse Physics-Informed Discovery of Empirical Relations (SPIDER) leverages recent advances in model discovery such as the weak evaluation of derivatives, symmetry-covariant libraries, and model agnostic regression to learn physics-informed PDEs from spatiotemporal data. We apply this method to a suspension of kinesin-driven microtubule bundles confined to an oil-water interface. We search six distinct tensor libraries in various irreducible representations of physical symmetries for hydrodynamic equations to consider every possible low-order coupling between the flow velocity and the nematic orientation. A complete interpretable model is found for our experiment outside of topological defects.

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MS223

Combining Data-Driven and Physics-Based Approaches to Predict, Understand, and Control Active Matter Dynamics

Active materials could enable materials with lifelike properties, but are typically unstable to chaotic dynamics that do not perform useful functions. Robust control strategies are needed to drive active materials into states that do perform desirable functions. However, this requires accurate dynamical models, which are unavailable for most systems. We combine data-driven techniques, physics-based models, and control theory to address this challenge for light-activated active nematics, in which activity is optically controlled in space and time. The challenge is to determine the spatiotemporal light sequence that drives the system into a desired behavior. I will describe two complementary approaches to this end. First, we use sparse regression to discover optimal physics-based continuum models directly from experimental data. The method reveals the contributions of different physical mechanisms and quantitatively estimates experimental parameters, but requires approaches to mitigate measurement errors. Then, we combine optimal control theory with the discovered model to compute optimal spatiotemporal activity profiles. We show that active materials can be driven into arbitrary behaviors, including those that that do not correspond to dynamical attractors. Second, we develop a model-free controller based on deep reinforcement learning (DRL), which is capable of driving active materials into arbitrary states.

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MS223

Interplay of Active Nematic Defects and Flow Structures

Active nematics are orientationally-ordered materials that convert energy from their surroundings to exert mechanical forces that drive the material out of equilibrium. Through the feedback between orientational order and active flows, macroscopic features emerge, such as coherent flow structures and a steady-state population of topological defects. This talk will demonstrate the existence of a strong cross-field constraint between motile $+1/2$ defects and contours of the flow field, where vorticity and strainrate balancetermed viscometric surfaces. Through experiments of microtubule-kinesin-based active nematics and nematohydrodynamic simulations, we establish the importance of these contours as paths for $+1/2$ defect dynamics, which influence the handedness of defect trajectories and the sites of defect pair creation and annihilation. We show through a series of models that the constraint is maintained through an interdependence of viscometric surfaces, $+1/2$ defects, and line-like structures of nematic bend deformation. These results highlight the importance of mesoscale nematic structuresbeyond isolated point defectsin shaping the emergent flows and provide a framework for studying complex defect behaviours in three dimensions.

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MS223

Dynamics and Interactions of Topological Defects in Active Nematic Liquid Crystals

Active nematics are active fluids in which the microscopic constituents and active forces exhibit nematic order. These systems manifest many fascinating phenomena such as active turbulence in unconfined systems or maximally mixing states and vortex lattices in confinement. In these dynamical states the behavior of topological defects, singular points in the nematic order, are equally as fascinating, and in many cases are intrinsically coupled to the observed macroscopic flows. In this talk I will present an approximate, analytical model for the velocity of topological defects in two-dimensional active nematics. The velocity may be decomposed into contributions from the Coulomb interaction between defects, advection from flows generated by active stress, and the deflection of defects in shear flow. I will present an analysis of the model for the interaction between just two defects, which reveals various phenomena such as the corotation of two positive defects, an effective attraction between two negative defects, and a critical unbinding length and impact parameter for two defects of opposite winding. Finally, I will show how the model may be scaled up to include arbitrary numbers of defects, and present results for multiple positive defects in confinement which exhibit braiding behaviors similar to those seen in recent experiments.

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MS224

Capturing Climate Claims: A Computational Text Analysis of Energy Company Press Releases

Over the past decades, the framing of climate change in public discourse has shifted significantly, from an emphasis on scientific uncertainty to concerns about economic costs of action and skepticism about policy effectiveness. Due to the major role that the energy industry has in the unfolding discourse around climate change, this project examines how the industry frames climate change over time. Integrating unsupervised and supervised approaches to text analysis, this project computationally analyzes 23 years of press releases from the five largest US energy companies ExxonMobil, Chevron, Marathon Petroleum, Phillips 66, Valero Energy. First, I use a classifier to filter the passages that are about climate change. Then, I use a topic model and qualitative analysis to examine the emergent topics over time. Finally, informed by the topic model and literature on corporate environmental framing, I define five frames and use GPT to search for their appearance within the energy company press releases. My analysis demonstrates that American Energy companies tend to frame climate change in terms of market demand for clean energy and techno-solutionism, and that these frames change in usage over time.

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MS224

Tracing the Displacement of the Human Appropriation of Net Primary Production (HANPP) Through Trade

Trade networks are geographic super-structures that create economic and ecological linkages between unexpected places. Though the qualitative nature of this relationship is well-documented, efforts to map these connections are complicated by the proprietary nature of trade data and the complexity of resource transformation through supply chains. However, understanding these teleconnections is critical to develop evidence-based policy that considers system-level impacts of proposed changes. This study represents one attempt to determine spatial relationships between distant commodity consumption and the local ecosystem impacts of extractive industries in the continental U.S. We focus on an indicator of human-arbitrated ecosystem pressure called Human Appropriation of Net Primary Productivity, or HANPP. HANPP measures the amount of photosynthetic products (in tons of carbon) harvested from an ecosystem through activities like agriculture or land use change. We calculate HANPP for livestock grazing, timber harvesting, and crop production in U.S. counties and link these to specific commodities in the U.S. trade network using a combination of mathematical frameworks, which allow us to quantify embodied HANPP (eHANPP) for dozens of commodity types. The goal of this research is to illustrate how networks of regions create localized ecosystem impacts and to foster a systems-oriented policy approach that accounts for unexpected consequences of local land use change.

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MS224

Operationalizing More Realistic Decision Making in Climate Economy Models: A Boundedly Rational Approach

Many models project future global temperature while ignoring feedbacks between the climate system and human behavioral and social systems. Prior research has shown that linking models of human behavior can significantly modify future climate compared to models using extrinsic climate scenarios. We describe our efforts to model the interactions of climate and social systems, focusing on the nature of risk perception and its role in determining climate policy. We couple a standard economic growth model with a climate model in a system dynamics framework. Economic activity produces emissions of GHGs, which drive changes in climate that lead to damages affecting economic growth. Rather than a benevolent social planner with perfect information who determines an optimal path of emissions, in our model, decisions about emissions reduction are driven by human risk perception and associated changes in attitudes and behavior shaped by the experience of extreme weather events. In modeling risk perception, we consider the interplay between climate factors - the size and number of extreme events and cognitive processes - salience, biased assimilation, recency, habituation, reactivity, and social contagion. Together, these factors determine investment in greenhouse gas abatement. Our results to date suggest a set of distinct future global temperature pathways than presented in previous linked models, even with similar assumptions on population growth and technological change.

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MS225

Time-Harmonic Wave Propagation in Periodic Half-Spaces

We consider the 2D linear Helmholtz equation in presence of a periodic half-space. A numerical method has been proposed by Fliss, Cassan, Bernier (2010) to solve this equation under the critical assumption that the medium stays periodic in the direction of the interface. In this case, a Floquet-Bloch transform can be applied with respect to the variable along the interface, thus leading to a family of closed waveguide problems. The purpose of this work is to deal with the case where the medium is no longer periodic in the direction of the interface, that is, if the periodic half-space is not cut in a direction of periodicity. We use the crucial (but non-obvious) observation that the medium has a quasiperiodic structure along the interface, namely, it is the restriction of a higher dimensional periodic structure. Accordingly, the idea is to interpret the studied PDE as the restriction of an augmented PDE in higher dimensions, where periodicity along the interface is recovered. This so-called lifting approach allows one to extend the ideas by Fliss, Cassan, Bernier (2010), but comes with the price that the augmented equation is non-elliptic (in the sense of the principal part of the differential operator), and therefore more complicated to analyse and to solve numerically. Numerical results will be provided to illustrate the method. Finally, if time permits, we will discuss the difficulties arising from the extension of this method to the nonlinear Helmholtz equation.

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MS225

Dispersive Hydrodynamics in a Quantum Droplet Bearing Environment

We demonstrate the controllable generation of distinct types of dispersive shock waves emerging in a quantum droplet bearing environment. Dispersive regularization of the ensuing hydrodynamic singularities occurs due to the competition between mean-field repulsion and attractive quantum fluctuations. The classification and characterization of these features are achieved by deploying Whitham modulation theory. Our results pave the way for unveiling a multitude of unexplored coherently propagating waveforms in such attractively interacting mixtures and should be detectable by current experiments.

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MS225

Nonlinear Excitations in Nonlocal Lattices

This talk investigates the breather formation in multi-dimensional lattices with slowly decaying nonlocal coupling. Using variational methods, we characterize the precise relationship between the key parameters involved-dimension, nonlinearity, and the nonlocal parameter αthat define positive excitation thresholds; the symmetry-breaking of translation in discrete lattice systems stipulates that the total power of a ground state be above a certain threshold, which we discuss in the nonlocal setting. In the anti-continuum regime, a unique family of ground states determines these thresholds, with spatial decay properties that vary continuously with α. We give analytic formulas for the excitation thresholds that grow polynomially in the coupling strength near $\kappa = 0$. Additionally, we analyze the dispersive wave dynamics, identifying a critical discontinuous transition in the time decay behavior of these waves as α crosses $\alpha_c = 1$. We provide numerical evidence that localized initial data with sufficiently large mass evolve into a localized breather-like component and a slowly decaying radiation. This work provides insights into the spatial and temporal decay patterns essential for understanding localized structures in lattice systems.

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MS225

Dispersive Estimates for a Dirac Equation with a Domain Wall

In this talk we will introduce a one dimensional Dirac equation which interpolates between two phase shifted constant coefficient equations at $x = \pm\infty$. Such equations arise in the study of topologically protected states for one dimensional quantum materials. This Dirac operator depends continuously on a parameter τ which measures the relative shift between the limiting operators. When $\tau = 0$ the operator has an edge resonance which leads to slow dispersive decay of the solutions, while for $\tau \neq 0$ no such resonance exists and solutions decay more rapidly. We derive a τ dependent bound which smoothly interpolates between these two different rates of decay. If time permits, we will discuss a related model where the dislocation parameter is time dependent and observe that one may observe even slower local decay estimates.

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MS226

Euler-Riesz Systems: High-Friction Limit and Compensated Integrability

The aim of this talk is twofold. First, we explain how to rigorously justify the high-friction limit of Euler-Riesz systems towards corresponding aggregation-diffusion equations. The methodology used in this analysis is the relative entropy method, where we consider dissipative weak solutions of the Euler-Riesz system and strong solutions of the limiting equations. Secondly, we explain how the compensated integrability theory yields higher integrability estimates for the density of Euler-Riesz systems. Additionally, this yields a bridge between PDEs and harmonic analysis through the study of a bilinear fractional integral operator.

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MS226

A Mathematical Journey Through Biological Optimal Transportation Networks

We propose a mesoscopic modeling framework for optimal transportation networks with biological applications. The network is described in terms of a joint probability measure on the phase space of tensor-valued conductivity and position in physical space. The energy expenditure of the network is given by a functional consisting of a pumping (kinetic) and metabolic power-law term, constrained by a Poisson equation accounting for local mass conservation. We establish convexity and lower semicontinuity of the functional on appropriate sets. We then derive its reduced

Wasserstein gradient flow, taken with respect to the tensor-valued conductivity variable only. Particular emphasis is posed on the steady states of the system. Finally, we derive the gradient flow of the constrained energy functional with respect to the Fisher-Rao (or Hellinger-Kakutani) metric, which gives a reaction-type PDE. Then, we introduce a macroscopic generalization of the mesoscopic model. This one is a self-regulating processes modeling biological transportation networks. Firstly, we write the formal L 2 - gradient flow for the symmetric tensor valued diffusivity D of a broad class of entropy dissipations associated with a purely diffusive model. Finally, we discuss well-posedness of the macroscopic system and present several numerical experiments.

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MS226

Influence of Vegetation Patterns on Wildfire Propagation

Climate change is increasing the frequency and intensity of wildfires, while altering vegetation patterns that serve as fuel for these fires. Understanding the dynamics of wildfire propagation, particularly the rate of spread, is essential for developing effective strategies to mitigate fire risks. This talk introduces a physics-based wildfire model that captures the interaction of opposing mechanisms, leading to emergent travelling wave behavior. We discuss the emergent travelling wave solutions by analytical methods, and investigate the role of drought-related factors, such as humidity, on fire dynamics. In particular, heterogeneous vegetation patterns found in dryland, driven by limited water availability and inclined terrain, lead to heterogeneous fuel distribution, which significantly influences wildfire spread. Simulations show the influence of those patterned vegetation on the rate of fire spread.

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MS227

Generalization Bounds for Learning Inverse Operators in PDEs

This study investigates the theoretical and empirical performance of learning-based methods for solving a class of inverse problems arising in partial differential equations. Focusing on scenarios where partial information about a solution is extended to the full domain, the work establishes provable generalization guarantees for operator learning frameworks. Theoretical insights are validated through a range of examples spanning various well-known PDE models.

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MS227

Kernel Methods for the Approximation of the Eigenfunctions of the Koopman Operator

The Koopman operator provides a linear framework to study nonlinear dy- namical systems. Its spectra offer valuable insights into system dynamics, but the operator can exhibit both discrete and continuous spectra, complicating direct computations. In this paper, we introduce a kernel-based method to con- struct the principal eigenfunctions of the Koopman operator without explicitly computing the operator itself. These principal eigenfunctions are associated with the equilibrium dynamics, and their eigenvalues match those of the lin- earization of the nonlinear system at the equilibrium point. We exploit the structure of the principal eigenfunctions by decomposing them into linear and nonlinear components. The linear part corresponds to the left eigenvector of the systems linearization at the equilibrium, while the nonlinear part is obtained by solving a partial differential equation (PDE) using kernel methods. Our approach avoids common issues such as spectral pollution and spurious eigen- values, which can arise in previous methods. We demonstrate the effectiveness of our algorithm through numerical examples.

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MS227

A Dynamical Systems Perspective on Measure Transport and Generative Modeling

Generative modeling via measure transport can be effectively understood through the lens of dynamical systems that describe the evolution from a prior to the prescribed target measure. Specifically, this involves deterministic or stochastic evolutions described by ODEs or SDEs, respectively, that shall be learned in such a way that the respective process is distributed according to the target measure at terminal time. In this talk, we show that this principled framework naturally leads to underlying PDEs connected to the density evolution of the processes. On the computational side, those PDEs can then be approached via variational approaches, such as BSDEs or PINNs. Using the former, we can draw connections to optimal control theory and recover trajectory-based sampling methods, such as diffusion models or Schrdinger bridges - however, without relying on the concept of time reversal. PINNs, on the other hand, offer the appealing numerical property that no trajectories need to be simulated and no time discretization has to be considered, leading to efficient training and better mode coverage in the sampling task. We investigate different learning strategies (admitting either unique or infinitely many solutions) on multiple high-dimensional multimodal examples.

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MS228

Unusual Bifurcations in a Delayed SIRS Model In-

duced by Immune System Boosting

We consider an epidemiological model that includes waning and boosting of immunity. Assuming that repeated exposure to the pathogen fully restores immunity, we derive an SIRS-type model with discrete and distributed delays. First, we prove the usual results, namely that if the basic reproduction number $\mathcal{R}_0$ is less than or equal to 1, then the disease-free equilibrium is globally asymptotically stable, while for $\mathcal{R}_0 > 1$ the disease persists in the population. The interesting features of boosting appear with respect to the endemic equilibrium, which can undergo multiple stability switches by changing key model parameters. We construct two-parameter stability diagrams and show that increasing the delay can stabilize the positive equilibrium. As $\mathcal{R}_0$ increases, the endemic equilibrium can pass through two distinct instability regions separated by Hopf bifurcations. A particularly interesting situation is when a branch of periodic orbits connects a super- and a subcritical Hopf bifurcation from the endemic steady state. Our results show that the dynamics of infectious diseases with boosting immunity can be more complex than most epidemiological models and require careful mathematical analysis.

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MS228

Numerical Methods for Distributed Delay and Renewal Equations

Numerical Methods for Distributed Delay and Renewal Equations abstract: A common feature of population models are cumulative effects of dynamical variables (such as resources or size distributions) in the past. This results in equations that have the form of renewal equations or delay-differential equations with distributed delay. Notably, the distributed delay is typically not just an integral over the past state, but a solution of differential equations which have the history segment as an inhomogeneity in their right-hand side. Even in simple didactic examples such as the growth model for daphnia analysed by Diekmann this results in multiple nested integrals over state history segments with state-dependent threshold delays. The presentation will show how one can perform basic numerical bifurcation analysis for these problems with DDE-Biftool and give some convergence results for numerical methods.

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MS229

Effects of Disorder on Neural Network Dynamics and Computations

Structural disorder has been reported to promote ordered network dynamics in various complex systems (Zhang et al. 2021 PNAS). In neuroscience, technological developments have led to massive data sets for cell-type-resolved brain structure. These data sets revealed a previously underappreciated level of neural heterogeneity, suggestive of high levels of structural disorder at the level of nodes in neural networks (Scala et al. 2021 Nature). In this work, we provide novel insight into the effects of neural heterogeneity on the dynamics and computations in spiking neural networks. We derived a set of mean-field equations which allows us to relate the heterogeneity of spike thresholds across neurons directly to the macroscopic network dynamics. We show via the mean-field equations that the heterogeneity of inhibitory interneurons plays a crucial role in shaping the dynamic regimes of neural circuits: heterogeneous inhibitory interneuron populations preserve the dynamic repertoire of local excitatory populations, whereas homogeneous interneurons overwrite excitatory dynamic repertoires and facilitates synchronized dynamics. Furthermore, we find that neural heterogeneity directly controls the encoding and function generation capacity as well as the dimensionality of spiking neural networks. Together, our results suggest that neural heterogeneity is an important control variable for computational states in neural networks.

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MS229

Heterogeneity Extends Criticality and Antifragility

While studying rank dynamics, we have found a universal pattern across a broad variety of phenomena: more relevant elements change their rank slower than the majority of elements. Our hypothesis was that this temporal heterogeneity provides a balance between robustness (slow) and adaptability (fast) similar to criticality, but without the need of fine-tuning parameters. With this motivation, we have studied the effect of different types of heterogeneity (structural, temporal, and functional) in complex systems, and shown that each of these "extend" criticality. Moreover, heterogeneity seems to also extend antifragility the ability of systems to benefit from perturbations. We have also used heterogeneity as a simple strategy to improve search algorithms. A question remains open: how to find "optimal" heterogeneity?

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MS229

Heterogeneity-induced Coherent Multi-pulse Dynamics in Laser Arrays

The ability to generate high-power, controlled pulses in semiconductor lasers and laser arrays is of fundamental theoretical and practical significance, with applications spanning multiple fields. Conventional pulse generation typically relies on external mechanisms such as strong modulation, unilateral injection, saturable absorbers, or unidirectional forcing. Here, we demonstrate that large external-cavity laser arrays, driven solely by direct current and subject only to optical feedback and non-local time-delayed coupling, can exhibit coherent multi-pulsing dynamics through engineered frequency heterogeneity. We show that this heterogeneity induces coherent multi-pulsing across the array at high bias currents, enabling multi-GHz operation, high peak power, and near-perfect phase synchronization. Through analytical and numerical analysis, we uncover a multi-pulse generation mechanism governed by two-cluster formation and heterogeneity-induced inter-pulse oscillations, which can be described by a non-autonomous Adler-type equation. These findings introduce a new framework for understanding and designing controllable pulsing dynamics in large-scale semiconductor laser arrays.

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MS229

Optimal Flock Formation Induced by Heterogeneity

The study of flocking in biological systems has identified conditions for self-organized collective behavior, inspiring the development of decentralized strategies to coordinate the dynamics of swarms of drones and other autonomous vehicles. Previous research has focused primarily on identical (or nearly identical) agents, owing to the widely held assumption that inter-individual differences inhibit consensus. Here, we examine the role of the heterogeneity among agents and find that suitable inter-individual differences can in fact promote consensus. We show that this counterintuitive effect can be leveraged to improve the performance of various collective tasks, including flock formation, target tracking, and obstacle maneuvering. In systems with communication delays, heterogeneity can enable convergence even when flocking is unstable for identical agents. Our results challenge existing paradigms in multiagent control and establish system disorder as a mechanism to promote collective behavior in flocking dynamics.

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MS230

Scalable Methods for Nonlocal Problems

The naive discretization of nonlocal operators leads to matrices with significant density, as compared to classical PDEs. This makes the efficient solution of nonlocal models a challenging task. In this presentation, we will discuss ongoing research into efficient hierarchical matrix assembly and geometric and algebraic multigrid preconditioners that are suitable for nonlocal models.

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MS230

Evolution of Large Spikes Clusters in the Gierer-Meinhardt sSystem

Pattern formation for a wide class of reaction-diffusion systems often leads to a solution consisting of multiple spikes. Here, we consider the mean-field limit of many spikes in the prototypical Gierer-Meinhardt model, and derive the effective equation for density evolution of a spike cluster. In the absence of any heterogeneity or boundaries, we obtain a novel porous-media-type PDE, $\rho_t = \left(e^{-1/\rho}\right)_{xx}$ that captures the cluster density as it spreads. When heterogeneities are present, they introduce an additional advection term in the mean-field limit and can “pin’ the spike cluster, stopping its spread.

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MS230

Levy Flight Search Processes in 2D Geometries and the Corresponding Green’s Functions

We discuss Levy flight search processes in various two-dimensional geometries, highlighting how the geometry of the search domain impacts search time, and contrasting the search time to that of Brownian search. Central to the analysis is the computation of a certain Green’s function of fractional Laplacian operators - we discuss a hybrid analytic-numerical algorithm for accurately computing the regular part of this Green’s function. This Green’s function can be useful in other problems involving localized features and the fractional Laplacian.

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MS232

Tail Behavior-Aware Reduced Order Models, with Application to Subsurface Simulation

Over-pressurization in subsurface reservoirs increases the risk of leakage and induced seismicity. Standard reduced order models (ROMs) aim to accurately resolve the mean model behavior, but may be inaccurate for distribution tails corresponding to extreme (but important) model behavior. We develop ROM methods capable of capturing such tail behavior. To achieve satisfactory accuracy for distribution tails using the standard proper orthogonal decomposition (POD) requires that tail samples are contained in the snapshots, and that a large number of POD modes is used. We propose two changes to the standard POD by i) using a weighted inner product that emphasizes relevant tail samples; (ii) generating extreme samples to be added as snapshots.

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MS232

Efficient Symmetry-Driven Diffusion Models for Wideband Inverse Scattering

The wideband inverse scattering problem is a classical inverse problem that uses scattered waves to infer the refractive index (media) in the Helmholtz equation. Classical PDE-based optimization methods face challenges with instability, high computational costs, and diffraction limits. We propose leveraging a conditional diffusion model to examine this classical problem from a deep learning perspective. Specifically, inspired by classical back-projection and filtering procedures, we factorize the score function of our conditional diffusion model into a physics-based latent representation and a convolutional neural network. In this training process, we respect the equivariance properties inherent to the physics problem and conduct optimization over a compressed space with a designed rank structure. Our framework empirically provides sharp reconstructions and even recovers sub-Nyquist features in multiple-scattering regimes. It also features low sample and computational complexity, with the number of parameters scaling sub-linearly with the target resolution and maintaining stable training dynamics.

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MS233

One Controller to Rule Them All? Simplifying Control with Koopman Operators

Efficiently learning to control dynamical systems from data hinges on rich but effective representations, whose construction remains underexplored. This talk presents a universal framework for transfer (Koopman) operator-based representations using reproducing kernel Hilbert spaces (RKHS), covering system identification and convex control design. In many cases of interest, the control design is entirely explicit and does not even require an optimization problem solver at all. Our entirely data-driven control design interfaces with controlled diffusion processes and requires no knowledge of the system dynamics or cost functions. The RKHS theory uses novel kernel mean embeddings (KMEs) to estimate Markov transition operators leading to operator-theoretic Hamilton-Jacobi-Bellman (HJB) recursions relying on the (stochastic) Koopman operator. Our kernel HJB (kHJB) overcomes the curse of dimensionality of traditional dynamic programming and delivers globally optimal feedback laws. Extending the kHJB approach, we propose physics-informed (PI) learning in infinite-dimensional RKHS by incorporating diffusion dynamics and samples of drift and control dynamics. The PI-kHJB fills a critical gap in existing methods by inducing physics-informed reproducing kernels, facilitating sample-efficient control design. The approaches are validated on examples ranging from synthetic ODEs to robotic simulators, demonstrating the efficacy of our data-driven optimal controllers.

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MS233

Koopman Theory with Sparse Kernel Methods

A representation of the Koopman operator can be constructed using reproducing kernel Hilbert space theory, which is related to embedding conditional probability distributions in said Hilbert space. Kernels provide a flexible and nonparametric machinery to implicitly construct basis functions, and can be applied to nonlinear dynamical systems defined on Euclidian spaces, but also other domains such as time-delayed sequences, strings or graphs. One of main disadvantages that arise in the kernel framework, is that the computational demands and memory requirements grow quickly with the number of training points, limiting the direct implementation to problems with at most a few thousand data points. By implementing sparsity and regularization techniques inspired by regression models based on Gaussian processes, we show that not only can the computational demands be significantly reduced, but the resilience of the numerical algorithm against sensor noise can be improved.

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MS233

Control of Complex Network Dynamics with Koopman: Tweaking Local Interactions for Desired Emergent Dynamics

The Koopman operator framework bridges data-driven and model-based control theory, integrating traditional control techniques with modern data-driven paradigms. This talk explores applying Koopman spectral analysis to control complex networks where individual node dynamics are known, but emergent behaviors transcend local interactions. We present a novel approach using physics-informed spectral approximation of Koopman operators to address challenges in controlling large-scale, nonlinear networked systems. By manipulating local interactions to achieve global behaviors without explicit knowledge of the network structure, we use skew-adjoint transformations of the Koopman generator and kernel-based smoothing to develop a robust method for identifying coherent patterns and dynamical features crucial for control strategies. Our approach ensures asymptotic consistency, facilitating stable control across varying network scales. We show how it enables systematic study of stability and attraction basins in nonlinear systems, revealing connections between Koopman eigenfunctions and intrinsic characteristics like unstable periodic orbits. This method is computationally efficient and reliable, overcoming instability often associated with pure data-driven approaches like reinforcement learning.

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MS234

Navigating Alzheimer's: Multimodal Learning Models for Disease Classification Via Pet Brain Imaging

Alzheimers disease (AD) is a neurodegenerative disorder that affects cognition and daily function. Over half of mild cognitive impairment (MCI) cases progress to dementia within five years, with AD as the most common outcome. Early and accurate detection of cognitive decline (CD), including AD and MCI, is crucial for effective patient care. This study employs PET imaging and deep learning for improved CD diagnosis. A multimodal model integrates PET features (PCANet, CNN) with numerical quantification data (DNN). Two fusion methodscanonical correlation analysis and direct concatenationcombine these modalities for machine learning classifiers. The model is tested on [18F]FDG PET scans from 252 subjects (118 cognitively normal, 134 CD: 70 MCI, 64 AD) from the Alzheimers Disease Neuroimaging Initiative. In 5-fold cross-validation, DNN outperformed CNN and PCANet in accuracy. Combining DNN and PCANet further improved accuracy and reduced variability. The fusion of PET imaging and quantification data enhances diagnostic performance beyond single-modality methods, offering a promising framework for CD classification with reduced data dependency.

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MS234

Neural Dynamics of Reversal Learning in the Prefrontal Cortex and Recurrent Neural Networks

In probabilistic reversal learning, the choice option yielding reward at higher probability switches at a random trial. To perform optimally in this task, one has to accumulate evidence across trials to infer the probability that a reversal has occurred. In this study, we investigated how this reversal probability is represented in cortical neurons by analyzing the neural activity in the prefrontal cortex of monkeys and recurrent neural networks trained on the task. We found that, in a neural subspace encoding reversal probability, its activity represented accumulation of reward outcomes, resembling a line attractor. The reversal probability activity at the start of a trial was stationary and stable consistently with the attractor dynamics. However, during the trial, the activity was associated with task-related behavior and became non-stationary, thus deviating from the line attractor. Fitting a predictive model to neural data showed that the stationary state serves as an initial condition for launching the non-stationary activity, suggesting an extension of the line attractor model. The non-stationary trajectories were separable showing that they can represent distinct probabilistic values. In sum, our results show that cortical networks encode reversal probability in stable stationary state at the start of a trial and utilize it to launch non-stationary dynamics that accommodates task-related behavior while maintaining the reversal information.

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MS234

Supervised Learning for Cardiac Disease Detection from Ecg Sequence Using Topological Data Analysis

ECG data is a time-series dataset representing heartbeat signals, commonly used for diagnosing anomalous heart behavior. In this study, we apply topological data analysis (TDA) to ECG data based on Fourier analysis. Fourier modes serve as multi-parameters; in particular, we employ exact multi-parameter persistent homology to identify the optimal filtration space where the most relevant features are extracted. These features are then utilized for anomaly detection using machine learning methods. Since these features are derived from the optimal space, these are superior classification performance compared to conventional TDA approaches for ECG data.

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MT1

A Practical Guide to Modeling with Higher-Order Networks

See description

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MT1

A Practical Guide to Modeling with Higher-Order Networks

See description

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MT2

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MT2

A Practical Guide to Modeling with Higher-Order Networks

This minitutorial will introduce participants to higher-order networks: why they are important, when to use these representations, and what structure and dynamics emerge from these networks. Networks have been used in the study of dynamical systems including epidemic spreading, opinion dynamics, synchronization, and game theory. The structure of a network influences the way that it behaves as a system, and we can connect these structural properties to its dynamical behavior. Network science, however, primarily considers pairwise networks, which assume that all interactions occur between two individuals or entities. However, for many empirical systems such as social networks, chemical reaction networks, co-authorship networks, and ecological systems, interactions can involve more than two entities. Higher-order networks remove this pairwise restriction and model group interactions of any size, known as higher-order interactions. This approach offers new challenges and opportunities for modeling dynamical systems. This minitutorial will introduce participants to the structure of higher-order networks, then connect the structure of higher-order networks to common dynamical models. These concepts and examples will be put into practice in the second half of the tutorial through an interactive software demonstration, using the XGI python package.

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MT3

Nonlinear Spectral Reduction for Equations and Data

See description

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PP1

A Theoretical Framework for Spatially-extended Neural Models with Slowly Evolving Parameters

Single-cell biophysical neural models are naturally written as systems of ordinary differential equations (ODEs) with time-scale separation, and this feature has a strong influence on their dynamical repertoire. A mathematical multiple time-scale theory for neural excitability, and for the generation of complex neural rhythms such as mixed mode oscillations or bursting, has been developed for single-cell models, but little is known at the level of neural populations, and for spatially-extended neural networks. A major obstacle towards exploring time-scale separation in networks of neurons is the lack of a comprehensive Singular Perturbation Theory for spatially-extended models and infinite-dimensional dynamical systems. In this poster, we present progress in this direction, with specific applications in neural field models. We study neural field models in which a (possibly large) number of parameters are varying on a slow time scale compared to neural activity. For these systems, we develop from scratch an analytical theory analogous to Fenichel theory for ordinary differential equations. We use a Lyapunov-Perron type approach, rooted in functional analytical methods, which can be adapted to other infinite-dimensional problems, such as Partial Differential Equations subject to slowly-varying parameters. The poster gives an overview of the theory, and provides an example based on neural field models available in the literature.

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PP1

Coarsening and Pattern Formation in Solids

Coarsening is a process where small features agglomerate together to form larger and larger features, eventually limited only by the size of the system. It can happen in materials science, where small voids in a metal join together to create large voids, eventually causing brittleness. In contrast, in pattern formation, structures (stripes and hexagons) form with a characteristic length scale largely independent of the size of the system. We examine a two component Cahn-Hilliard model that shows a transition from coarsening behaviour to pattern formation. We study the linear and nonlinear features of this model to explore this transition.

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PP1

Parameter Sensitivity, Identifiability, and Estimation of the Lorenz System

Ordinary differential equation (ODE) models commonly used to represent real-world phenomena, often include unknown parameters that must be estimated from observational data. Estimating these parameters, however, can be computationally expensive. Parameter identifiability analysis determines whether model parameters can be uniquely determined from observed data, whereas sensitivity analysis examines how variations in model parameters impact its output(s). Thus, parameter identifiability and sensitivity inform parameter estimation. In this study, we use the Lorenz system as a case study in both chaotic and non-chaotic regimes. We determine parameter identifiability with respect to all the variables, conduct sensitivity analysis and apply a nudging technique to estimate the unknown parameters using synthetic data. We demonstrate that sensitivity and identifiability analyses provide valuable insights for interpreting estimation outcomes in both the chaotic and non-chaotic regimes.

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PP1

New Kolmogorov Bounds in the Clt for Random Ratios and Applications

We develop techniques for determining an explicit Berry Esseen bound in the Kolmogorov distance for the normal approximation of a ratio of Gaussian functionals. We provide an upper bound in terms of the third and fourth cumulants, using some novel techniques and sharp estimates for cumulants. As applications, we study the rate of convergence of the distribution of discretized versions of minimum contrast and maximum likelihood estimators of the drift parameter of the OrnsteinUhlenbeck process. Moreover, we derive upper bounds that are strictly sharper than those available in the literature.

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PP1

Early Identification and Analysis of Time Series of Mice

We will give an overview of our work analyzing continuously measured telemetry data from mice experiments. In broad terms, we wish to understand the effect, variability, and heterogeneity of mouse response to infection or treatment. In one set of experiments, we study how infectious disease these coarse-level measurements and evaluate early warning and anomaly detection systems. In another set of experiments, we study the impact of female mice with a daily treatment during pregnancy. In both situations, body temperature and quantized activity are sampled on the order of 1 to 5 minutes. We will overview the tools and success thereof to this data, including time-delay embedding, unsupervised and/or online signal processing, kernel methods, and clustering and pattern matching of time series, and statistical machine learning. Time permitting, we will also discuss the possibility of coupling minimal ODE models (e.g. minimal immune system models) to observed telemetry data. This is based on both previously published and ongoing work with collaborators.

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PP1

Autonomous AI-Controlled Rocket for Lunar Launch and Earth Re-Entry

This project focuses on developing an AI-powered rocket capable of launching from the Moon and landing on Earth, demonstrating the feasibility of AI in managing complex lunar and terrestrial operations. Launching from the Moon presents unique challenges including: reduced gravity, lack of atmosphere, and the need for precise trajectory control to safely re-enter Earths atmosphere. By employing an AI-controlled system, this project aims to optimize launch, navigation, and landing through real-time adjustments. The goal of this research is to showcase an AI-driven system that can autonomously handle both lunar launch and Earth landing, laying the groundwork for future missions that require minimal human oversight. The small-scale prototype is designed to autonomously control lunar lift-off, manage trajectory corrections in space, and execute a controlled descent upon Earth re-entry. The rocket is powered by a dual-thrust engine system and guided by a Raspberry Pi microprocessor, which processes real-time data from sensors, including accelerometers, gyroscopes, altimeters, and thermal cameras. This project provides a significant step forward in aerospace technology by demonstrating AIs potential to autonomously conduct critical operations in varying gravitational environments. Success in this endeavor could influence future lunar missions, supporting autonomous cargo and potentially crewed journeys between celestial bodies promoting safer, more efficient space exploration.

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PP1

Hardware Fingerprints from Solvable Chaotic Circuits

Symbolic dynamics is a powerful approach to the analysis of chaotic dynamical systems. If a symbol sequence is produced by a generating partition, then a known map's initial condition can be resolved from the sequence. Conversely, the symbol sequence produced from a known initial condition is informant on the structure of an unknown map. We apply symbolic techniques to differentiate between a set of identically assembled chaotic oscillator circuits, whose running waveforms embed iterates of a unimodal map. Specifically, we aim to use the circuit as a hardware security primitive producing a fingerprint a bit stream capable of unique device self-identification. Accurate symbolization of iterates is enabled by tapping the folding mechanism of the oscillator circuit, which is coupled to the map generating partition. The differences in map structures due to small manufacturing variances are revealed through iteration of the map, due to the exponential sensitivity of the chaotic dynamics. This exponential sensitivity is preserved through the conjugate symbolic dynamics, and used to inform the device fingerprint.

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PP1

Geometric Analysis of a Gene Regulatory Model with Hill Functions of Varying Steepness

We study a gene regulatory model represented by a planar nonlinear system of ODEs, initially introduced by Plahte and Kjglum (2005). The model contains two Hill functions with steepnesses controlled by two independent small parameters $0 < \varepsilon_1, \varepsilon_2 \ll 1$. As long as ε_1 and ε_2 are positive the system is smooth, but in the singular limit $(\varepsilon_1, \varepsilon_2) \to (0, 0)$ we obtain a piecewise smooth (PWS) system. We carry out a multi-parameter singular perturbation analysis based on geometric singular perturbation theory (GSPT) combined with iterative blow-ups in phase- and parameter space, leading to a comprehensive bifurcation analysis of the model. In each of the regimes $\varepsilon_1 \ll \varepsilon_2$, $\varepsilon_1 \approx \varepsilon_2$ and $\varepsilon_1 \gg \varepsilon_2$ a distinct two-parameter bifurcation diagram is presented. In particular, we show that the existence of periodic solutions and bistability within the system depends on the relative steepnesses of the Hill functions.

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PP1

Towards Detecting Dynamical Changes in Noisy Ecological Spatial Data with Computational Topology

A challenge in the study of population dynamics is developing methods for predicting changes that could lead to decline/extinction. This becomes increasingly important as the environment continues to change and numerous species become both directly and indirectly affected by human-driven climate alteration. Here, we identify topological indicators of change that emerge in time series of spatial data, e.g., satellite images. We use persistent cubical homology for pattern quantification, and explore how different measurements such as Betti numbers change over time. A crucial part of our methodology has been reducing stochastic noise in the data while simultaneously preserving topological features. Work is ongoing, but preliminary results show that different types of stress on an environment have different topological signatures.

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PP1

State-Dependent Delays in Feedback Loops: Insights from An El Nio-Southern Oscillation Model

Delay differential equations (DDEs) are widely used to model time-delayed feedback processes, which play crucial roles across diverse fields, including control theory, laser dynamics, and climate science. The delays in these models are commonly taken to be constant; however, this is a modelling assumption because delays often depend on the state of the system. Here, we explore a particular state-dependent DDE model of the El Nio-Southern Oscillation, a climate phenomenon that is responsible for hard-to-predict changes in sea surface temperature and atmospheric conditions across the equatorial Pacific. This model incorporates both delayed negative feedback and seasonal forcing, where the implicit state dependence of the delay emerges naturally from the finite propagation speeds of oceanic processes. Surprisingly, our results show that, on its own, this type of state-dependent delayed feedback produces dynamics identical to those of the corresponding constant-delay system.

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PP1

A Mathematical Model at the Wildlife-Livestock-Human Interface to Predict the Implications of Measures to Control Bovine Tuberculosis

The complex and dynamic interactions among wildlife, livestock, and humans create environments conducive to the emergence of new diseases or the reemergence of existing ones. Such outbreaks pose a significant threat to multiple host species, and in the case of cattle infections, farmers face substantial economic losses. Our study focuses on Mycobacterium bovis (M. bovis), the primary cause of bovine tuberculosis in domestic and wild animals as well as humans. To understand the transmission dynamics of M. bovis among wildlife, livestock, and human populations, we propose a mathematical model that incorporates cross-species transmission between livestock, wildlife, and humans, as well as transmission routes through contaminated environments. We have selected the state of Michigan, USA, as a case study to estimate the model parameters and assess the disease burden of bovine tuberculosis. From the sensitivity and scenario analysis, we identified the key drivers of disease burden and observed that increasing the efficacy of vaccination and culling in wildlife, as well as enhancing surveillance, vaccine efficacy, and culling in livestock, reduces the transmission of bovine tuberculosis among wildlife, livestock, and human populations. Due to the chronic nature of bovine tuberculosis, continuing vaccination and increasing efficacy in both wildlife and livestock are important to reduce the overall disease burden at the wildlife-livestock-human interface.

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PP1

Countoscope for Active Matter: Determining Non-Equilibrium Diffusivities Without Msds

In 1916, Smoluchowski proposed a new method to determine the diffusion coefficient of particle suspensions without having to use particle tracking, which is required for conventional mean-squared displacement (MSD) methods. Instead, you can simply count the number of particles within the observation field of a microscope, and measure how this number fluctuates with time as particles stochastically jump in and out of the field due to Brownian motion. This method was recently revived for equilibrium diffusion of 2D colloidal suspensions (Mackay et al, PRX 2024). Now, we extended this method to study non-equilibrium diffusion of active suspensions. We study swimming microorganisms and measure their number fluctuations to extract their non-equilibrium diffusion and their motility characteristics. To test this method, we compare directly with the conventional MSD technique, and we also compare our results with simulations of active Brownian particles (ABPs) and further extensions of Smoluchowskis theory. This technique could become a new standard in the field for dense, active, and living suspension dynamics.

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PP1

Non-Uniformity of Synchronization in the Zero Lyapunov Exponent Limit

We consider the product of i.i.d. random matrices sampled according to a probability measure $\mathbb{P}$ on $GL(d, \mathbb{R})$ in a synchronizing regime characterized by a negative top Lyapunov exponent λ. We study the transition to a zero top Lyapunov exponent regime under variation of the probability measure $\mathbb{P}$. We consider the number of back-and-forth escapes from a ball around the origin (describing non-uniformity of the synchronization) and prove that the expected number of such escapes scales as λ^{-1} in the $\lambda \to 0$ limit.

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PP1

Oscillations in Excitable Media on Networks

Excitable media model many real-world phenomena, displaying wave initiation and annihilation. A simple model for excitable media is the Greenberg-Hastings cellular automaton (GHCA), with dynamics discrete time steps and a discrete phase space. A result by J. Gravner , H. Lyu , and D. Sivakoff (2016) studies this cellular automaton on networks and determines which graphs and initial conditions lead to persistent oscillations. We propose a simple system of ODEs on directed graphs that mimics the dynamics of GHCA. Our model uses a discrete network to couple variables in a system of ODEs, the resulting dynamics are continuous and much richer than those of the GHCA. We present results on absence of oscillations in trees and emergence of oscillations in graphs that contain cycles.

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PP1

Extraction of Coherent Sets in Aperiodically Driven Flows

Coherent sets are time-dependent regions in the physical space of nonautonomous flows that exhibit little mixing with their neighborhoods, robustly under small random perturbations of the flow. They thus characterize the global long-term transport behavior of the system. We propose a framework to extract such time-dependent families of coherent sets for nonautonomous systems with an ergodic driving dynamics and (small) Brownian noise in physical space. Our construction involves the assembly and analysis of an operator on functions over the augmented space of the associated skew product that, for each fixed state of the driving, propagates distributions on the corresponding physical-space fibre according to the dynamics. This time-dependent operator has the structure of a semigroup (it is called the Mather semigroup), and we show that a spectral analysis of its generator allows for a trajectory-free computation of coherent families, simultaneously for all states of the driving. Additionally, for quasi-periodically driven torus flows, we propose a tailored Fourier discretization scheme for this generator and demonstrate our method by means of three examples of two-dimensional flows. Lastly, we discuss how our work connects to open problems about the mixing behavior of fluid flows.

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PP1

Design of Experiments Facilitates Development of Digital Twins in Systems Biology

A digital twin is a well informed, predictive, digital representation of a physical system, with multiple industrial applications including energy, transportation, and healthcare. Model-based design of experiments (MBDoE), and the creation of a biological digital twin, have the potential to save tremendous time for experimenters. Further, digital twins will streamline the gain of new information within the life sciences community. This contribution discusses opportunities and challenges of creating digital twins for biological systems. Specifically, we discuss nonlinear parameter estimation and MBDoE for developing, validating and optimizing models for fruit fly development, including mechanical (e.g. growth, wing shape) and chemical (e.g. aging, channels) properties. Laboratory experiments are conducted with fruit flies (i.e. Drosophila melanogaster) to generate high-content informative data. The generated data is used to estimate mechanical and chemical model parameters through parameter estimation. We then use Pyomo.DoE, an open-source, MBDoE package in Python, to evaluate which candidate experiments are optimal with respect to information content. By optimizing the experiments conducted to obtain the necessary information, MBDoE facilitates the production of the final predictive digital model. Finally, we discuss opportunities to translate digital twins for model organisms to study human disease patterns, like Parkinsons, through the evaluation of genetic variation.

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PP1

Predicting General Election Outcomes from Primary Results at the Precinct Level

In the United States, polling data are collected at the state level, but election results vary substantially within states (e.g., between rural and urban areas). Unlike polls, election results are often available at the precinct level, and these fine-scale data can provide insight into how primary elections, general elections, and voter turnout are related at a granular level. Using primary and general election data at the precinct level for past presidential races, we model the relationship between the degree of partisan consensus (entropy) in the primaries and each partys under- or over-performance in the general election. These patterns give insight into voter turnout decisions and provide a fine-grained method for forecasting general elections.

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PP1

Slow Passage Through the Busse Balloon Predicting Steps on the Eckhaus Staircase

In dryland ecosystems, a large, dense area of vegetation may fracture into several smaller patches to adapt to conditions unable to support uniform covering. Further as conditions worsen, the ecosystem may organize to reduce the vegetation it supports by removing patches. Motivated by such phenomena, we study the complex Ginzburg-Landau equation, which admits spatially periodic solutions whose stability depend on a parameter. We let this parameter slowly vary in time, destabilizing solutions with high wave number and leaving those with smaller wave number viable. In this setting, it is observed that an initially stable periodic solution is eventually forced to transition to a solution with a smaller wave number, analogous to an ecosystem electing to remove patches in our motivating example. We develop an understanding of the dynamics of an initially stable spatially periodic solution under the destabilizing effect of the drifting parameter. In particular, we make predictions about the time delay of solution transition after the onset of instability, characteristic of slow passages through bifurcation. We also establish conditions that allow one to predict which stable state the system will select once a transition occurs. In particular, transition delay and pattern selection are shown to be heavily influenced by spatio-temporal resonances in the linearization at the initial condition.

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PP1

Automatic Speaker Recognition Based on Visibility Graph Analysis on the Spectral Domain

Visibility graphs, as a framework for transforming temporal signals into complex networks, have proven to be a robust analytical tool within network science, applicable across diverse scientific domains. This study investigates the utility of visibility graphs in the spectral domain for speaker recognition, employing a dataset comprising vocalizations of the five Spanish vowels produced by multiple adult participants. Utilizing the source-filter model of speech production, we computed the frequency spectrum to capture formants, which are influenced by the resonant characteristics of the vocal tract. Our findings indicate that spectral profiles exhibit consistent intra-speaker properties that reflect individual vocal tract anatomies, while revealing inter-speaker variability. Visibility graphs are constructed from these spectral representations and extracted various graph-theoretic metrics to elucidate their topological features. These metrics were integrated into feature vectors for each vowel, subsequently utilized to train an ensemble of decision trees, achieving high accuracy in speaker identification. Critical topological features were identified as significant differentiators among speakers. This research underscores the efficacy of visibility graphs for spectral analysis and their promising application in speaker recognition, offering insights into the robustness and potential integration of this methodology within real-world recognition systems.

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PP1

Computing Escape Rates from Periodic Orbits in Chaotic Hydrogen

Placing a hydrogen atom in parallel electric and magnetic fields results in chaotic classical trajectories and complex quantum energy states. We are interested in studying the exponential escape of classical trajectories to infinity which model ionizing electron trajectories. This escape rate can be computed using periodic orbit theory, which converges absolutely with the inclusion of all unstable periodic orbits. The technique sums over each orbit and weights the dynamical contribution by the orbits length and stability eigenvalue. This motivates us to acquire a complete set of orbits up to a reasonable topological length. We choose system parameters so the dynamics are entirely hyperbolic and so for a given topological length there are a finite number of orbits. We then use the theory of heteroclinic tangles to create a finite Markov partition of phase space and acquire a complete set of orbits up to a topological length of ten. This modest set of orbits is shown to be sufficient to accurately compute the escape rate for a range of energy values. The same set of orbits can be utilized in a semiclassical context to compute complex quantum energy states. In the fully quantum case, each energy eigenstate decays in time in a similar way to the classical ensemble of trajectories escaping in time. Relating classical trajectory ensembles to quantum eigenstates in this way allows for periodic orbits to be used to probe the classical-quantum transition.

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PP1

Modeling Dynamical Audio-Tactile Interactions in Stream Segregation

We present a new computational model of audio-tactile interactions to investigate the role of tactile stimulation in auditory stream segregation. We examine how tactile pulses synchronized with specific tones in a sequence alter the likelihood of perceiving integrated or segregated auditory streams. Based on experimental findings, the dynamical model captures interactions within auditory and tactile neural circuits including recurrent excitation, mutual inhibition, adaptation, and noise. It builds on a framework where distinct neural populations process high- and low-frequency sounds in the auditory cortex. The model includes populations responding to two specific frequencies as well as an intermediate one. This model offers insights into cross-modal effects on stream segregation and predicts neural behaviour under varying tactile conditions. Separate psychoacoustic experiments validate the model, showing that tactile pulses synchronized with specific tones enhance perceptual segregation, while pulses synchronized with both tones promote integration. These results suggest that selective tactile stimulation dynamically modulates tonotopic organization within the auditory cortex, in agreement with neurophysiological studies. Our findings imply that cross-modal synchronization, particularly with carefully timed tactile cues, could optimize auditory perception with potential applications in auditory assistive technologies aimed at enhancing speech recognition in noisy settings.

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PP1

Oscillatory Dynamics Is Generic in Models for Fate Choice in Neural Crest Stem Cells and Confuses Pseudotime Reconstruction Algorithms

Historically, the development of an embryonic cell is often thought of as being analogous to a ball rolling down a potential landscape in genotypic space, in which the coordinates correspond to gene expression levels, trajectories represent alternative developmental pathways, and differentiated cell states correspond to different attracting equilibria. Changes in the shape of the landscape allow different cell fates to be selected. This imperfect paradigm has led to competing alternative views of fate choice in neural crest stem cells: the Direct Fate Restriction and Progressive Fate Restriction hypotheses. In recent work we have attempted a reconciliation of these through our proposed Cyclical Fate Restriction model which robustly, and intriguingly, points to temporal oscillations as an intermediate step in the cell differentiation process. In this poster we demonstrate that the emergence of oscillations is extremely robust to parameter choices, and also that single-cell RNA-seq data produced in the oscillatory regime would substantially confuse traditional pseudotime trajectory reconstruction algorithms.

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PP1

Rigorously Classifying Stability of Stationary Pulses to a Fourth-Order Scalar PDE Via the Maslov Index

The stability of stationary pulse solutions to PDEs has long been studied using the associated linearized ODE. One notable result from Sturm-Liouville theory directly relates the number of unstable eigenvalues to the number of local extrema, or conjugate points, of the pulse. Recently, there has been an effort to develop an analogous stability result for fourth-order scalar equations using the Maslov Index. It has been shown that for a particular parameterized family of fourth-order Hamiltonian ODEs, there exist infinite families of multimodal pulse solutions classified by the number of small-amplitude oscillations between larger peaks (modes) in the spatial profile. Furthermore, there is numerical evidence that the number and parity of modes in this classification is directly associated with the number of conjugate points of the pulse solution, independent of the parameter. In this poster we will rigorously prove this result for the unimodal – or primary – orbit, which we then expand upon for the complete set of multimodal solutions. The results of this project, characterizing the stability of pulses immediately from a visual profile, are intended to serve as an extension of classical Sturm-Liouville theory to fourth-order scalar PDEs such as the Swift-Hohenberg equation.

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PP1

Delayed Loss of Stability in a Hopf Bifurcation: Rediscovering M. Shishkova's Proof

We consider the stability problem for complex valued ODEs

$$u'(t) = (\varepsilon t + i)(u(t) - \varepsilon t) + F(u(t) - \varepsilon t)$$

with initial data at $t_0 < -1$. Here ε is a small positive parameter, and the function F has real analytic components (but need not be complex analytic) and vanishes at least quadratically at the origin. The special case $F(u) = |u|^2 u$ was studied by M. Shishkova in 1973, who showed that solutions stay in ϵ-neighborhoods of the moving equilibria $u_0(t) = \varepsilon t$ until $\varepsilon t = 1 - O(\sqrt{\varepsilon})$, long after these equilibria have lost stability at $t = 0$ in a Hopf bifurcation. Shishkova's proof used an iteration scheme for solutions that are extended into complex time. Later fundamental work on this phenomenon, especially by A. Neishtadt since the late 1980s, has relied on different approaches. In this contribution, we show how Shishkova's original proof can be cast in a modern and rigorous framework. Our approach gives the more precise result that the solution stays ε^2-close to the solution of the corresponding linear problem ($F = 0$) until $\epsilon t = 1 - O(\sqrt{\varepsilon})$, and it suggests further generalizations.

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PP1

Leveraging Topological Data Analysis for Uncovering Hidden Dynamical Systems

This study employs Topological Data Analysis (TDA) to identify hidden dynamical systems by exploring the diverse topological shapes of trajectories influenced by underlying hyperparameters. Recognizing that each dynamical system configuration manifests unique topological features, we use TDA to categorize systems based on these invariant properties. By analyzing the persistence of topological features and tracking changes in trajectory structure, we can effectively distinguish systems and detect bifurcation points. This framework not only clusters dynamical systems with similar topological signatures but also provides insights into the underlying dynamics, allowing for better understanding of how parameter shifts lead to qualitative changes in system behavior. Our approach combines manifold learning and TDA, providing a novel framework for system classification through computational topology on the low-dimensional manifold. This poster showcases biological applications (e.g., electrocardiogram (ECG) data set), illustrating the robustness of TDA in identifying critical system transitions with minimal a priori knowledge of system equations.

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PP1

Invariant Sets of Differential Equations with Bounded Noise

Randomness in differential equations is often introduced by adding Gaussian noise. However, because Gaussian noise is unbounded, it allows trajectories to reach arbitrarily high speeds, which may be unrealistic in practical applications. In certain contexts, it is more realistic to model noise as a bounded process. This bounded noise imposes a constraint such that only a limited set of points can be reached within any finite time. Calculating these reachable sets is highly complex due to the infinite-dimensional nature of the noise, if all possible noise realisations were to be considered. However, techniques from control theory can be employed to selectively examine specific noise realisations. This approach leads to a higher-dimensional, but deterministic, dynamical system that is closely related to the original, lower-dimensional random differential equation. In particular, it enables the description of forward-invariant sets in differential equations subject to bounded noise. I will present the derivation of the deterministic system and its connection to the original noisy system, with a focus on the time evolution of reachable sets and the regularity of the boundaries of invariant sets.

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PP1

Harnessing Single-Cell RNA Sequencing for Modeling Endocrine Cell Electrical Activity

Modeling endocrine cell electrical activity is essential for understanding hormone secretion dynamics. While endocrine cells are known to express a diversity of ion channels, data-driven modeling is hampered by the fact that evidence for various channels come from disparate experiments. Single-cell RNA sequencing (scRNAseq) data enables a systematic approach by providing a comprehensive inventory of genes coexpressed in specific cell types. We leverage scRNAseq data to construct models of pituitary cell electrical activity, incorporating gene expression-driven representations of ionic currents. We analyze pituitary cells from scRNAseq datasets to identify expressed ion channel genes, mapping them to corresponding model currents to build a data-driven model. Because mRNA levels may not directly correlate with ion channel densities, expression data is used to guide choices of currents to include in the model. Quasi-Monte Carlo sampling of model parameter space with GPU-accelerated simulations is used to identify non-trivial parameter regions with biologically plausible activity patterns. Finally, investigation of gene correlations and parameter redundancies motivates a structured approach for model reduction, leading to simplified models amenable to analysis. This approach aims to produce data-driven models of excitable cells that balance biological accuracy with mathematical tractability.

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PP1

Stability of Quasi-Simple Heteroclinic Cycles and Applications

A heteroclinic cycle is a sequence of trajectories connecting a set of equilibrium points (or more general invariant subsets) in a topological circle. An interest is taken in their dynamic behaviour determined by the way they are stable. The stability of heteroclinic trajectories can be quantified by the local stability index. We develop a method to compute this index for a general class of robust heteroclinic cycles called quasi-simple heteroclinic cycles. A heteroclinic cycle is quasi-simple if its heteroclinic connections are one-dimensional and contained in flow-invariant spaces of equal dimensions. We ensure that the dynamics between two connected equilibria is encoded in a transition matrix whose entries only depends on the eigenvalues of the linearisation at the outgoing equilibrium. The local stability index is calculated by taking the rows of the (products of) suitable transition matrices. Our method applies to a wide range of heteroclinic cycles arising in game-theoretic models, population dynamics and neural systems. Stability properties are particularly useful to describe the dynamics near heteroclinic networks. We illustrate our results with quasi-simple cycles that are part of the heteroclinic network of the coupled Rock-Scissors-Paper system. These cycles are shown to be as stable as possible for a wide range of parameter values, depending on the players' payoff received for a tie.

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PP1

Stability Analysis of a Neural Mass Model

In our work we analyze the nonlinear dynamics of two coupled neuron sub-populations using neural mass models. We focus our analysis on the Coombes-Byrne mean-field model, which has been shown to capture seizure-like dynamics. [Coombes & Byrne, Next Generation Neural Mass Models, Nonlinear Dynamics in Computational Neuroscience, 2019.] We first study the single population model, and produce two-parameter stability diagrams, using a combination of Lyapunov exponent calculation and bifurcation analysis. This divides the parameter space into regions of oscillatory and quiescent behavior. Using the results of this analysis, we identify ten distinct classes of the two sub-population model. They are classified according to the nature, oscillatory or quiescent, of each sub-population, as well as the type of coupling between them. We identify two relevant classes of the model and perform a similar analysis, producing a range of stability diagrams for pairs of coupling parameters. We find that the system goes through a range of supercritical Hopf and torus bifurcations, producing complex behavior including seizure-like dynamics. In parallel, we have formed a computational model for a large number of theta neurons, on which the mean-field reduction is based. We implement the mean parameters of the neural mass model through a Lorentzian probability distribution in the network model. We then compare the results of our large network model to those of the Coombes-Byrne model.

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PP1

Ricci Flow-Guided Autoencoders in Learning Time-Dependent Dynamics

We present a manifold-based autoencoder method for learning dynamics in time, notably partial differential equations (PDEs), in which the manifold latent space evolves according to Ricci flow. This can be accomplished by parameterizing the latent manifold stage and subsequently simulating Ricci flow in a physics-informed setting, matching manifold quantities so that Ricci flow is empirically achieved. With our method, the manifold is discerned through the training procedure, while the latent evolution due to Ricci flow induces an accommodating representation. We present our method on a range of experiments consisting of PDE data that encompasses desirable characteristics such as periodicity and randomness. By use of a geometric flow, we sustain a canonical manifold latent representation for all values in the ambient PDE time interval. Furthermore, the Ricci flow facilitates qualities such as learning for out-of-distribution data and robustness. We showcase our method by demonstrating these features.

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PP1

Construction of Symplectic Systems Based on Parameter-Drift Hamiltonian-Like Maps

The behavior of deterministic dynamical systems under parameter drift is an area of active research. Studying these nonautonomous systems provides insights into time-dependent phenomena, such as climate change, where parameterslike CO_2 levelsvary over time. Recently, low-dimensional Hamiltonian-like systems have been explored under parameter drift. However, characterizing their dynamics remains challenging due to their inherent nonautonomous nature, which limits the use of traditional methods in dynamical systems. In this work, we address these challenges by employing the extended phase space approach to eliminate explicit time dependence in parameter-drift Hamiltonian-like systems. Based on the standard nontwist map with parameter drift, we construct a generating function for a new autonomous map in this extended space, where the new coordinate represents the iteration time. The resulting autonomous map not only closely mirrors the dynamics of its parameter-drift counterpart but is also truly symplectic, since it is obtained by a canonical generating function. This approach enables the calculation of traditional dynamical indicators, such as Lyapunov exponents, facilitating the identification of important phase space structures.

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PP1

A Transfer Operator Based Computational Study of Reacting Fluids

In many industrial applications one aims for efficient chemical reactions, for example in a continuous stirred tank reactor. We model and analyze mixing processes of chemical substances by a transfer operator method. In practice, we represent fluids by density vectors. These are evolved by means of a stochastic transition matrix, which is obtained as a numerical approximation of a transfer operator. In a further step, we model the reaction of the fluids by specific update rules of the density vectors. We consider closed and open example systems and study different chemical processes such as competitive consecutive reactions.

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PP1

Collision Avoidance and Vegetation As Drivers of Collective Motion in Australian Plague Locusts

Locusts are agricultural and ecological pests that cause billions of dollars in crop damage each year. Due to global climate change, outbreaks may become more severe and frequent, and outbreaks have already appeared in regions that were not previously susceptible. We study hopper bands of the Australian plague locust (Chortoicetes terminifera), dangerous juvenile locust structures that are kilometers wide and can advance hundreds of meters per day, destroying vegetation in their path. While mathematical models of hopper bands have traditionally focused on social interactions between locusts, recent models have focused on vegetation as a major contributor to observable band properties. Yet these models likely overestimated the speed of a hopper band because recent data suggests that locusts slow down to avoid collisions with other locusts. We improve estimates of the speed and shape of a hopper band by adding collision avoidance between locusts to existing locust models. Using agent-based and PDE models, we examine how collision avoidance between locusts influences the shape and speed of hopper bands. We also use field data to determine how long it takes a locust to get around another locust in the way, estimating parameters critical to this model. These results may advance our understanding of collective structures in locusts and could benefit locust control efforts, which are essential to maintaining food security and may become more crucial as the world warms.

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PP1

Topological Entropy of Swiss-Roll Attractors

Dynamical systems undergoing saddle-saddle bifurcations often exhibit comodulatory oscillatory activity on multiple timescales. Attractors in such systems can be viewed as “Swiss-roll attractors’ by the use of template theory. We use the Milnor-Thurston kneading theory to study the topological complexity of templates for various Swiss-roll attractor appearing in neuronal and laser models.

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PP1

Invasion Fronts in the Presence of a Slowly-Varying Parameter

Nonlinear reaction-diffusion equations have been shown to exhibit a wide variety of behaviors, including invasion fronts and pattern formation. We study properties of invasion fronts in the presence of a slowly-varying and increasing parameter. Using the prototypical Fisher-KPP equation, we find this parameter induces novel acceleration of the front which is different than what is predicted by a frozen-coefficient marginal stability analysis. Using a Green’s function analysis we not only obtain accurate leading-order predictions for the front location but also obtain the second order correction. We make rigorous our results using comparison principles and a scaling-variables analysis. We also examine pattern-forming fronts in a slowly-varying complex Ginzburg-Landau equation. Here we use a similar analysis to predict the slowly-varying oscillation frequency, and thus the local wavenumber, in the leading edge, and a Burger’s modulational analysis to characterize the wavenumber mixing in the wake.

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PP1

Resistance to Reinfection in a Host Undergoing Regular Viral Exposures

It is possible that ongoing circulation of virus in a population can impact host immune dynamics. In a model of within-host virus-immune system interaction, we examine the impact of regular inputs of virus via an impulsive model. For a naive host, after an initial infection, we observe that some patterns of viral exposure result in additional illness. Other patterns of exposure, even with regular viral inputs, appear to be protective against illness. We vary the time between exposures (the flow time) and the exposure size (the kick size), identifying flow-kick parameter combinations that result in no reinfection, in transient reinfection, and in ongoing reinfection. Analyzing this system as a map, we work to identify the bifurcation structure and to understand the basin of attraction of the no-reinfection state. We also analyze a continuous analog to the impulsive flow-kick system.

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PP1

Dynamics of An Electronic Relay-System with Delayed Bandpass-Filtered Feedback

Delay dynamics have wide relevance in fundamental science and technology due to the ubiquitous presence of feedback loops in which time lags arise because of natural processes, control interfaces, or performance limits of components. We present results from a well-controlled experiment that is representative of feedback systems with relays (switches) that actuate after a fixed delay. Notably, the system exhibits strong multi-rhythmicity, the coexistence of many stable periodic solutions for the same values of parameters. We then study the system dynamics analytically. The model we consider is a nonsmooth second-order delay differential equation that describes single-input single-output systems in which the delayed feedback is a band-pass filtered relay signal. We discuss how periodic solutions and bifurcations can be obtained by reducing the system to a set of finite-dimensional maps. We find good agreement between theory and experiment.

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PP1

Dynamics Induced by a Heteroclinic Network Comprising Five Nodes

Intransitivity plays an important role in ecological models of competition where no single species dominates. The behaviour of such models is organized by a heteroclinic network. A heteroclinic orbit is a solution that connects two equilibria of a system. A heteroclinic network is a union of several heteroclinic cycles, which are closed loops of heteroclinic orbits. The classic Rock-Paper-Scissors game is one example that serves as a basic model for competition between three species. When the game is translated into a system of differential equations in continuous time, it gives rise to a heteroclinic cycle that connects three equilibria, each of which represents the dominance of a single species. We consider a spatially extended model of intransitive competition between not three, but five species; the dynamics can be viewed as an expansion of the Rock-Paper-Scissors game with two additional strategies. In this game of Rock-Paper-Scissors-Lizard-Spock, each strategy beats two of the strategies and loses to the remaining two. The system contains more equilibria, which represent dominance of only a subset of the species; the resulting heteroclinic network contains several different heteroclinic cycles. We will introduce the model and convey the richness of possible dynamics close to the heteroclinic network. We will present examples of new periodic orbits that bifurcate from specific cycles in the heteroclinic network and show how they change as parameters vary.

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PP1

Photosensitivity and Neuronal Synchronization

Neurons are the fundamental building blocks of the nervous system. Computational modeling of neurons can provide a powerful tool to study neurological processes, including neurological disorders. Epilepsy, for example, is a nervous system disorder characterized by excessive brain activity, which includes abnormal neuronal synchronization. It affects around 50 million people worldwide and can have devastating disruptions in their lives. Despite advancements in diagnosis and treatment, no definitive cure exists. Computer simulation studies using quantitative neuron network models can help the understanding of brain functions under neuropathological conditions. The outcome may be useful not only in the development of detection but also, in the prevention of seizures. In this work, we focus on understanding the role of external stimuli in influencing neural synchronization and seizure onset. Using the Huber-Braun neuron model based on the Hodgkin-Huxley equations, we simulate a network of coupled neurons to analyze how action potentials are triggered and synchronized under different conditions. Specifically, we introduce flickering light as a stimulus to the model and examine how it interacts with temperature changes. Our results show how external triggers like light can interact to cause abnormal brain activity, giving us a clearer picture of how to better understand and manage stimulus driven seizures.

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PP1

A Random Flow-Kick Model of a Fire-Savanna Ecosystem

Wildfires can play a crucial role in the maintenance of ecosystems. This is the case for savannas, which are characterized by coexistence of grass and woody vegetation. We consider the flow-kick framework, proposed by Hoyer-Leitzel and Iams [Bull. Math. Biol. 2021], to model a savanna ecosystem. In their investigation, fires are represented as instantaneous, periodically applied disturbances (kicks) to the system, and between-fire recovery is modeled by a Lotka-Volterra dynamical system (flows). The periodic flow-kick model for fire disturbances leads to a map that they fully analyzed. It possesses a rich bifurcation structure, with different regimes of savanna bistability depending on model parameters related to fire intensity and frequency. We compare results of the idealized case of periodic fires to a model where fires have some random aspects to their timing, as done by Magnani, et al. [Am. Nat., 2023] in their studies of fire ecosystems. We use numerical simulation, combined with some analysis, to specifically show how the bifurcation structure is washed out when there is sufficient variability in fire return times. We also find large parameter regimes where this randomness leads to woody encroachment, which would have negative implications for savanna ecosystems that support livestock grazing. The larger challenge of appropriately modeling the distribution for fire severity, based on observational studies from long term ecological research stations, is also discussed.

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PP1

Koopman Analysis of the Singularly-Perturbed Van Der Pol Oscillator

The Koopman operator framework holds promise for spectral analysis of nonlinear dynamical systems based on linear operators. Eigenvalues and eigenfunctions of the Koopman operator, so-called Koopman eigenvalues and Koopman eigenfunctions, respectively, mirror global properties of the systems flow. In this paper we perform the Koopman analysis of the singularly-perturbed van der Pol system. First, we show the spectral signature depending on singular perturbation: how two Koopman principle eigenvalues are ordered and what distinct shapes emerge in their associated Koopman eigenfunctions. Second, we discuss the singular limit of the Koopman operator, which is derived through the concatenation of Koopman operators for the fast and slow subsystems. From the spectral properties of the Koopman operator for the singularl-perturbed system and the singular limit, we suggest that the Koopman eigenfunctions inherit geometric properties of the singularly-perturbed system. These results are applicable to general planar singularly-perturbed systems with stable limit cycles.

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PP1

A Dynamical Model of the Pyloric Central Pattern Generator

We describe a procedure for constructing a dynamical model of the crustacean pyloric cpg network with a view to studying the networks response to perturbations. The model is assembled using a modified Plant model neuron consisting of a system of Hodgkin-Huxley type equations. Synaptic dynamics are modeled using the alpha synapse as well as a recently developed logistic synapse model. The model captures key features of the pyloric 3-phase rhythm such as the proper order of bursting and lag between the pacemaker and its followers.

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PP1

Parameter Estimation in An Agent-Based Model of Zebrafish Using Pair Correlation Functions

In the skin of zebrafish, the iconic black and yellow stripe patterns emerge from the self-organizing interactions of brightly colored pigment cells. Several models have been developed that treat pigment cells as agents that are moving, competing with one another, and differentiating through stochastic rules. Here we consider a recent agent-based model of zebrafish patterns, and we apply pair correlation functions to quantitatively describe wild-type and mutant patterns. Using these summary statistics, we apply methods from Approximate Approximate Bayesian Computation (AABC) to estimate key parameters governing cell interactions in the agent-based model. We also discuss how parameter inference depends on the choice of summary statistic that we use, comparing non-spatial and spatial measurements.

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PP1

Patterns in the Wake of a Parameter Ramp

We study the formation of patterns in the light-sensitive CDIMA system in the presence of a slowly-varying opaque mask which induces a Turing instability as it moves through both 1 and 2 spatial dimensions. Previous work used a sharp mask to control the formation of patterns, whereas we study the behavior under a slowly-varying mask. Here the slowly varying parameter induces an asymptotically constant front from which Turing patterns can form in the wake of the ramp. We find through numerical simulation that the wave number selection curves under a slow-ramp significantly differ from those under a sharp parameter ramp. This is further confirmed using pseudo-arc-length continuation. We then study the relationship between the slowly-ramped CDIMA and an analogous complex Ginzburg-Landau equation. For the cGL equation, we use geometric singular perturbation theory and invariant manifold theory to construct pattern forming fronts and determine wave number selection curves. We observe a change in the shape of the manifold at a critical parameter value, determined by the absolute instability threshold of the trivial state. We use a WKB approximation to understand behavior up to and just past this critical parameter value as a means to understand the region where Fenichel theory fails and our invariant manifolds are no longer guaranteed to exist.

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PP1

Analysis of the Geometric Structure of Neural Networks and Neural ODEs via Morse Functions

In addition to classical feed-forward neural networks, neural ODEs, which can be viewed as an infinite depth limit of neural networks, have gained particular interest in recent years. We study the input-output dynamics of finite and infinite-depth neural networks with scalar output. In the finite depth case, the input maps under multiple non-linear transformations to the state of one output node. In analogy, a neural ODE maps a linear transformation of the input to a linear transformation of its time-T map. We show that depending on the structure of the network, the input-output map has different properties regarding the existence and regularity of critical points, which can be characterized via Morse functions. We prove that critical points cannot exist if the dimension of the hidden layer is monotonically decreasing or the dimension of the phase space is smaller or equal to the input dimension. If critical points exist, we classify their regularity depending on the specific architecture. We show that each critical point is non-degenerate if the graph of the neural network has no bottleneck or if the linear transformations of neural ODEs have full rank. The established theorems are comparable in the finite and infinite depth case and allow us to formulate results on universal embedding and approximation. Our dynamical systems viewpoint on the geometric structure of the input-output map provides a fundamental understanding of why specific architectures outperform others.

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PP1

Anchored Spirals in Sharp-Interface and Phase Oscillator Models

We present results on spiral waves in a sharp-interface model where a curve, anchored with a fixed angle at a disk, rotates with a constant speed, $c = V - D\kappa, \kappa$ curvature. We show the existence, stability and asymptotics in a limit where $0 < D \ll 1$. We also show preliminary results on existence and instability when $c = V - D\kappa + \kappa_{ss}$ with $D < 0$. From a different perspective, we also analyze the existence and stability in a phase dynamics approximation, $u_t = \Delta u + f(u)$ on the domain $r \leq |x| \leq R$, where $f(u) = f(u + 2\pi)$.

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PP1

Size-Structured Population Model with Distributed State in the Recruitment

Continuous structured population models are frequently used to study fundamental questions of population dynamics. These models assume that individuals are distinguished from one another by characteristics are often referred to as size in general. In the classical case, size-structured models are formulated in terms of a nonlocal hyperbolic partial di?erential equation describing the dynamics of the density $u(x, t)$ together with an initial value $u_0(x)$ and a boundary condition at $x = x_0$. The boundary condition describes the in?ow of newborns in the population. In most of these models, it is assumed that all the newborns have the same size x_0. However, the recruitment cannot be accurately modeled by simply imposing one boundary condition at the x_0. Population models with distributed states-at-birth thus were introduced and studied. Here we considered a general size-structured model where individuals may be recruited into the population at di?erent sizes. The recruitment of new individuals is demonstrated in the partial di?erential equation and modeled by a Lipschitz operator. we focus on the development of ?nite di?erence schemes to approximate the solution of the model. Further, all the new born individuals are assumed to have the same size in the classical size-structured model. This should be a special case of the model with distributed states-at-birth where the distribution of the new recruits concentrated at the smallest size.

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PP1

Stability and Attraction in ODEs – An Overview

Stability and attraction are crucial concepts in the study of dynamical systems, in particular ordinary differential equations. They help understand the dynamics by characterizing which states can be expected to dominate long-term behaviour in the sense that solution trajectories move towards them for a large set of initial conditions. Over the past decades several concepts have been developed to refine the classical notion of asymptotic stability, among these fragmentary and essential asymptotic stability. Such intermediate levels of stability are particularly useful when it comes to non-hyperbolic structures that attract a set of positive measure which is not a full neighbourhood. Furthermore, a stability index has been introduced and widely used, allowing for a local description of attraction/stability for a larger set, such as a heteroclinic cycle or network. In preparation of a review article on this topic we give an overview of these notions, their relations and some applications as well as open questions.

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PP1

Reduced-Order Modeling of Partial Differential Equations Using Equilibrium-Informed Neural Networks and Initial Transient Data

We use neural machine learning to construct reduced-order models for dynamical systems governed by partial differential equations that possess an inertial manifold. Specifically, we employ neural machine learning for three purposes: (1) to approximate the inertial manifold, (2) to define the dynamics on that manifold, and (3) to encode initial conditions onto the manifold. Assuming the inertial manifold contains an equilibrium point, each machine learning model is designed to incorporate the equilibrium and its linearization. First, an autoencoder neural network incorporates the tangent space. Second, a neural ordinary differential equation incorporates an oblique projection of the original system's linear dynamics. Finally, all models preserve the equilibrium at the origin without compromising universality. Unlike previous studies, which rely solely on post-initial transient data, we also utilize initial transient data to learn the encoding of initial conditions onto the inertial manifold. Specifically, this encoding is learned by formulating a supervised problem, where initial transient data is mapped to the backward-time solutions of the dynamics in the latent space. To demonstrate the efficacy of our method, we investigate three physically significant systems: a three-dimensional model of fluid flow past a circular cylinder, the complex GinzburgLandau equation, and the KuramotoSivashinsky equation.

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PP1

Climate Tipping Points: Insights from a Non-Equilibrium Thermodynamics Framework

With increasing climate warming, many Earth system elements are poised to undergo critical transitions or tipping. Reliable anticipation of these tipping elements is vital to inform policy decisions. Many of the current methods for tipping point detection are based on loss of resilience or 'critical slowdown of the system as it approaches a tipping point. However, these methods are prone to false alarms; the detected slowdown may instead be an artifact of gradual changes in system dynamics or nonstationary noise unrelated to tipping behavior. Here, we explore the efficacy of early warning signs (EWS) based on a non-equilibrium thermodynamic and dynamical framework analogous to the traditional statistical mechanical treatment of equilibrium phase transitions (Yan, H. et al., 2023). The model-free detection method relies on the increased microscopic time-irreversibility due to detailed balance breaking and the resultant increase in entropy production rate, preceding the onset of tipping or instabilities. We demonstrate that these EWSs are effectual for tipping point detection (bifurcation and rate-induced tipping) and are robust to the aforementioned false alarms, using idealized models for various climate tipping elements. These EWSs thus provide an alternative set of indicators for validating the approach of a tipping point.

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PP1

Bifurcations in the Swift Hohenberg Equation with Continuous Non-Smooth Nonlinearity

The Swift Hohenberg equation is a conceptual order-parameter model for pattern formation that captures the essential features of many different physical systems, including fluid dynamics (e.g., Rayleigh-Bnard convection), chemical reactions (e.g., Turing patterns in reaction-diffusion systems) and biological systems (e.g., predator-prey models or the formation of biological patterns like animal spots and stripes). In its standard terms it entails polynomial force terms, and we replace the monomials with general powers $|u|^\alpha$, for which the bifurcation analysis has not been done. Such terms are motivated by non-smooth hydrodynamic forces and models of ship maneuvering, shimmying wheel. Due to these non-smooth terms, the analysis cannot rely on direct Taylor expansion. Numerical studies show intruiging behaviour of the periodic roll-type solution of Swift Hohenberg equation and of the homoclinic snaking. The latter is a well-known phenomenon in the smooth case and concerns homoclinic solutions that correspond to convectons. This poster will mainly discuss the behaviour and the analysis of the periodic branch, and of the snaking branch.

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PP1

Tracking Bacterial Growth Using a Nonlocal Interfacial Model

Biological pattern formation has been extensively studied using reaction-diffusion and agent-based models. In this talk we will discuss nonlocal pattern forming mechanisms in the context of bacterial colony formation with an emphasis on arrested fronts. This will lead to a novel nonlocal framework to understand the interfacial motion in biological systems. We will then use this approach to model experiments for an interesting bacterial phenomenon.

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PP1

Kuramoto Oscillators with Higher-Order Interactions and Rotational Symmetry Breaking

Beyond the classic pairwise coupling, higher-order interactions have been shown to have a deep effect on the resulting dynamics of the network. A wide diversity of dynamical states have been observed in networks with higher-order interaction, including synchronized states, explosive transitions, and chimera states. We present a study of the Kuramoto model with higher-order interactions that break rotational symmetry of the original system. We use the Wanatabe-Strogatz approach to obtain a low-dimensional representation of the system. With the analysis of the reduced model we identify the different bifurcations, including transcritic, SNLC, heteroclinic, Hopf and homoclinic, and Bogdanov-Takens bifurcations. With the details of the solutions and bifurcations we obtained the phase diagram that divides the regions in the parameter plane in which different collective states are observed. These states include incoherent dynamics, traveling waves, oscillatory and stationary synchronized states, and also alternating chimera states. The emergence of spatiotemporal dynamics such as chimeras and traveling waves in networked systems has deep implications in different fields of science. We hope our results shed light into the underlying mechanism for the emergence of different spatiotemporal patterns, which may help studying these states in biological and realistic systems.

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PP1

Fault Estimation and Fault Tolerant Control for Networked Based Parabolic Nonlinear PDE Systems Against Cyber-Attacks and Disturbances

This study investigates the problem of fault estimation and fault tolerant control design for networked based parabolic-type nonlinear PDE systems in the presence of Neumann-type boundary conditions against cyber-attacks with faults and external disturbances. Primarily, Proportional integral based intermediate estimator is built to estimate the immeasurable states and faults occurring in the system. Moreover, the constructed estimator precisely facilitates for estimating the fault signals and system states in simultaneously. Besides this, the integral term in the proportional integral estimator offers greater design flexibility and higher resilience. Secondly, an intermediate estimator-based fault-tolerant control is devised by availing the information from the proportional integral-based fuzzy intermediate estimator, which aids in effectively compensating the faults arising in the system. Furthermore, by endowing Lyapunov stability theory, a set of sufficient conditions is developed in the frame of linear matrix inequalities to guarantee the augmented closed-loop system is stable. Subsequently, the explicit form of the desired proportional integral gain matrices is parameterized using the matrix inequality techniques. Finally, numerical example is utilized to show the effectiveness of the proposed method.

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PP1

Emergent Cooperative Strategies for Multi-Agent Shepherding Via Reinforcement Learning

The shepherding problem addresses a fundamental challenge in controlling large-scale dynamical systems: how one group of agents (herders) can collectively steer the dynamics of a larger group (targets) toward desired configurations. This has applications in fields like robotics and crowd dynamics [Long et al.,A Comprehensive Review of Shepherding as a Bio-Inspired Swarm-Robotics Guidance Approach,IEEE Trans. Emerg. Top. Comput. Intell.,2020]. While literature commonly assumes cohesive target behavior, few studies relax this, typically relying on heuristic models for herders [Auletta et al., Herding stochastic autonomous agents via local control rules and online target selection strategies, Auton Robot, 2022]. Here, we propose a decentralized multi agent reinforcement learning approach [Gronauer et al., Multi-agent deep reinforcement learning: a survey, Artif Intell Rev, 2022] to (i) relax target cohesion assumptions, (ii) reduce reliance on heuristics, and (iii) formulate the problem in an optimization framework for learning-based solutions. Our two-layer architecture features a low-level layer that controls each herder to corral and contain a target within a designated goal region, and a high-level layer that dynamically assigns each herder a target to drive. Cooperation emerges as herders autonomously select distinct targets. We extend this approach to large-scale systems by applying a shared policy trained on fewer agents, with each herder sensing subset of targets.

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PP1

Disturbance Compensation-Oriented Security Control Design for Switched Singular Semi-Markovian Jump Systems with Hybrid Cyber

Attacks

This study offers the framework to cope with the unified disturbance estimation and security control issue for singular switched semi-Markovian jump systems confronted with multiple delays, external disturbances and hybrid cyber-attacks. Further to precisely forecast the external disturbances, the modified equivalent input disturbance estimator is laid out at first. Specifically, the compensator has been embedded in the traditional equivalent-input-disturbance estimator. Added to this, the supplied disturbance compensation strategy pulled off a considerable amount of progress in the removal of disturbances. Secondly, taking advantage of this disturbance estimate information, the disturbance rejection controller is designed which assist in suppressing the disturbances in the system model under investigation. Therein, the control segment notably accounts for multiple attacks, thus rendering the systems security. In this context, multiple attacks encompass the both denial of service and deception attacks, which take place in a cohesive framework in a stochastic fashion and are independent of each other. Thirdly, sufficient criteria that ensure the primary goal of this investigation are put forth by using the linear matrix inequality method and Lyapunov stability theory. Finally, the simulation examples are offered, which show the potential of the design approaches and exhibit that the strategy enacted in this work can provide an adequate disturbance estimation.

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PP1

Recovering Islands from Their Shoreline with the Eikonal Equation

The evolution of the shape of natural landscapes such as islands can be modeled with a partial differential equation that incorporates tectonic uplift, soil diffusion, and fluvial erosion, the last of which describes the coupling of the erosion of soil due to runoff or debris flow with the specific catchment area. Under the assumptions that diffusion is negligible and the erosion is uncoupled with the specific catchment area, the steady-state problem reduces to the eikonal equation, a classical equation arising from geometric optics. Landscapes generated from the eikonal equation are characterized by having a constant hillslope, and are completely determined by the shape of the downstream boundary. Anand, Bertagni, Singh, and Porporato [Geophysical Research Letters, 2023] looked at four example landscapes (two Mediterranean islands, Mount Fuji, Japan, and a section of the Zanskar mountain range, India), and found good agreement between the eikonal model and real elevation data. We extend this analysis to a large number of islands across the globe, gauging the ability of the eikonal equation to recover the full topography of an island given only the shape of its shoreline. To compare the eikonal predictions to satellite elevation data, we make use of the Wasserstein, or Earthmover, distances, treating the real and generated islands as probability density functions.

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PP1

Assessing Insulin Sensitivity in An Adolescent Cohort Using the Oral Minimal Model

Puberty is associated with several major metabolic changes including decreased insulin sensitivity (SI). In combination with other risk factors, this change in SI can produce metabolic dysregulation in adolescents. Dynamic SI (SID) is related to SI and additionally incorporates the dynamics of insulin action to account for both the speed and the capacity of the insulin response. However, it is not known how SID changes during puberty. As a first step to address this question, we applied the oral minimal model (OMM) to data from an adolescent cohort to assess SI and SID. OMM is a differential equations-based model that describes interactions between glucose and insulin concentrations during a frequently sampled oral sugar tolerance test; OMM best-fit parameters provide sensitive estimates of an individuals SI and SID. We found that although SI and SID were generally correlated, SID may be more sensitive to changes in metabolic health. Improved understanding of changes in SI and SID in adolescence is needed to design and assess optimal therapeutic interventions for metabolic dysregulation in this population.

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PP1

Slowly, Then All at Once: Uncovering the Dynamics of a Catastrophe

Many natural and human complex systems evolve on a slow timescale and are stable with respect to external perturbations. However, these systems can experience sudden rapid departures from their natural equilibrium, known as tipping events, which often bring catastrophic and unrecoverable repercussions. Extreme paleoclimate events, ecosystems collapse and economic crises are some examples of dynamical systems evolving slowly around an equilibrium until a tipping point causes a fast, unforeseen critical transition outside the basin of attraction and onto a new, unhealthy state. An early-warning signal is a (often statistical) quantity that provides forewarning of a major tipping point based on the structure of the timeseries data while in hyperbolic regime. Precursing phenomena such as critical slowing down or flickering between alternative states in metastable regimes are easily captured by an increase in variance or skewness respectively. However they are limited to low-dimensional dynamical systems that do not include spatial information and pattern-forming instabilities. In this poster we will review the fundamental issues plaguing the application of early-warning signals theory for spatially-extended stochastic PDEs and introduce a novel, prototypical approach based on the escape time from a po-

tential well from a probabilistic perspective.

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PP1

Into the Wild: A Journey to Chaos in Four Dimensions

Wild chaos is a form of higher-dimensional chaotic dynamics that can only arise in vector fields of dimension at least four. We study wild chaos in a four-dimensional system of differential equations, which is a four-parameter extension of the classic Lorenz equations. Recently, Gonchenko, Kazakov and Turaev (2021) showed, via the computation of Lyapunov exponents, that this system has a wild chaotic attractor at a particular point in parameter space. We investigate how this wild chaotic attractor arises geometrically, performing a bifurcation analysis of the system in a two-parameter setting. As a starting point, we continue the one-parameter bifurcation structure of the classic Lorenz equations when the fourth parameter is switched on. We find that the well-known homoclinic explosion point of the Lorenz system unfolds and gives rise to infinite cascades of global connections in the four-dimensional system that are of Shilnikov type. These connections are formed by the unstable manifold of the origin, which still plays an essential role in the emergence of complicated dynamics in the system. We also compute the kneading diagram that encodes how this one-dimensional manifold repeatedly moves around a pair of equilibria. In combination with the direct computation of curves of global bifurcations, the kneading diagram provides insight that helps identify regions where wild chaos may occur.

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PP1

Pattern Formation Driven by Three-Wave Interactions with Two Critical Wavenumbers

Three-wave interactions (or resonant triads), where two wavevectors add up to a third, are present in many pattern-forming systems. They govern the dynamics close to onset and can be used to explain pattern-forming behaviour in the Faraday wave experiment and in coupled Turing systems. Considering problems with two critical wavenumbers, it is possible for two waves of a larger wavenumber to interact with a third wave of smaller wavenumber, and vice versa. Resonant triads with these two length scales can explain the presence of a wide variety of complex patterns such rhombs, superlattice patterns and quasipatterns, and even spatio-temporal chaos when many resonant triads interact with one another. Indeed, rotations of a single triad (by the angle separating these wavevectors) generates a second resonant triad, which can interact with the first due to the shared wavevector. We present an analysis of the patterns formed by a model PDE, an adaptation of the LifshitzPetrich equation with additional nonlinear terms. We use weakly nonlinear theory to draw comparisons between the patterns predicted by a system of ODEs and those observed in the PDE.

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PP1

The Effect of Silencing Noise on Noise-Induced Transitions under Periodic Forcing

The classic problem of noise-induced transitions between minima of a double-well potential, described by a Langevin equation, has also been extensively studied in the case where the double-well is periodically modulated. The periodic forcing introduces an additional time-scale to the problem, leading to different parameter regimes. The periodic forcing also modifies the metastable transition rate from that of the autonomous case [Chao, Duan, Wei. SIADS (2024)]. Moreover, it has been proposed that in certain regimes, the most likely transition path, identified through a (modified) Freidlin-Wentzell large deviation theory, can be associated with a particular phase of the forcing [Chen, Gemmer, Silber, Volkening. Chaos (2019)]. This observation is motivated by Earth system and ecological problems, where there is a question of whether tipping events are more likely to occur in a particular season of the year. In this work, we further explore the notion of a preferred tipping phase for a periodically forced Langevin equation, through numerical simulations where we periodically silence noise for short intervals of time. We explore how the phase of noise silencing changes the expected time of metastable transitions, and how it modifies the most likely transition path between stable periodic states. Identifying the phase where noise silencing drastically decreases the mean transition rate suggests seasons of higher-risk for tipping events in a problem.

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PP1

Inferring Insulin Secretion Rate from Discrete C-Peptide Data in Adolescents

Puberty is associated with several major metabolic changes including increases in insulin secretion. Although insulin secretion rate (ISR) cannot be measured directly, reliable inference of ISR has enabled the use of ISR-based met-

rics of pancreatic beta cell function. We recently developed a Bayesian hierarchical model (BHM) that incorporates physiological constraints to precisely infer continuous ISR profiles from discrete C-peptide data. By considering the logarithm of ISR as a Gaussian process, we construct physiologically meaningful, nonnegative ISR profiles along with ranges of certainty for each point in the prediction. Here, we apply this method to infer ISR profiles with uncertainty in an adolescent cohort and assess of beta cell function with ISR-based metrics including the area under the ISR curve, the maximum secretion rate, and the time to peak secretion. This work provides insights into ISR in adolescents and may facilitate early therapeutic interventions for individuals with impaired beta cell function.

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PP1

Precision Agriculture: Measuring Crop Per Drop Using the Internet of Things, Machine Learning, and Mathematical Modeling

Kidney beans comprise less than one percent of agricultural land usage so there is scant research performed on this crop. This gap results in farmers and agronomists relying on guides and heuristics when they decide to grow beans making this crop difficult to grow and putting it a disadvantage when competing with other, more well-researched, crops. This research was initiated by agronomists employed by a local kidney bean processor who wanted to know the link between irrigation and kidney bean yield. To address this problem a mathematical model consisting of a nonlinear system of three coupled ordinary differential equations (ODEs) to simulate plant growth, plant water availability, and reproductive biomass was developed. The biomass equation is approximated by a neural ODE as its output is driven by, not only, the dependent variables of the other two equations but also by historical yield data and field data. Researchers constructed and installed five data-collection stations in a 200-acre kidney bean field to obtain the data needed to calibrate the model. The stations contain sensors that collect weather and soil data that is uploaded to cloud-based storage. Additionally, kidney plants were grown in a greenhouse where the plants were separated into four sections and tended to by FarmBot, an automated farming system. This device also captured plant images for calibrating the plant growth model.

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PP1

Next Generation Power Electronics Enabled by Solvable Chaos

We present the design, simulation, and hardware validation of both buck-boost DC-DC converter and solvable chaotic oscillator circuits. Buck-boost converters are ubiquitous in nearly all electronic systems. One forthcoming issue involves the monitoring of fluctuations in power electronics to inform bad actors with sensitive data. In this work, we aim to obfuscate these fluctuations by bridging theory and design of buck-boost converter architectures to nonautonomous, solvable chaotic systems. Interestingly, these solvable chaotic systems aid design with closed-form solution and exhibit features that are strikingly similar to popular buck-boost converter designs. By redesigning a buck-boost converter through the lens of a solvable chaotic oscillator, we will be investigating the role of chaotic systems in protecting sensitive data (i.e. medical records, etc) against side channel attacks.

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PP1

Recovering Underlying Network Topology in Models of Opinion Dynamics

Multi-agent dynamical systems are foundational in modeling complex systems across numerous domains. While observing individual agent dynamics in real-world systems is often possible, enumerating the relationships between individual agents can be difficult. Therefore, inferring underlying network topology from data is key in enabling models of real-world multi-agent systems. From previous work, there exists an array of distinct model architectures for inferring underlying network topology from data. Despite this, many algorithms are fragile with respect to changes in underlying network structure, model dynamics, and availability of data. The goal of our work is to perform a systematic study of the effectiveness of network inference for various graph structures on synthetic data from a variety of well-studied models of opinion dynamics. We find particular shortcomings in the stability of these algorithms in certain situations, e.g., small changes in parameters for generative network models (such as ErdosRnyi) can result in large changes in the accuracy of inferred network structure.

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PP1

Contrarian Nodes Vs Coevolution: Two Opposite Forces in Complex Networks' Synchronization

It is well known that adaptative networks and coevolution phenomena are ubiquitous in real-world systems ranging from ecology and epidemiology to neuroscience, socioeconomics and technological systems and they enhance the synchronization in non-linear dynamics that occur on complex networks. On the other hand, the existence of contrarian nodes mitigates the formation of synchronization patterns in many dynamical systems on complex networks. In this poster, the interplay between these two opposite mechanisms is presented, by analyzing the synchronization of Kuramoto phase-oscillator model on complex networks that includes some coevolution mechanisms between nodes and links and the existence of a fraction of contrarian nodes that modifies the equilibrium state of the system.

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PP1

Parametric Resonance, Chaos and Spatial Structure in the Lotka-Volterra Model

We investigate the Lotka–Volterra model for predator-prey competition with a finite carrying capacity that varies periodically in time, modeling seasonal variations in nutrients or food resources. In the absence of time variability, the ordinary differential equations have an equilibrium point that represents coexisting predators and prey. The time dependence removes this equilibrium solution, but the equilibrium point is restored by allowing the predation rate also to vary in time. This equilibrium can undergo a parametric resonance instability, leading to subharmonic and harmonic time-periodic behavior, which persists even when the predation rate is constant. We also find period-doubling cascades and chaotic dynamics between the subharmonic and harmonic instabilities. If we allow the population densities to vary in space as well as time, introducing diffusion into the model, we find that variations in space diffuse away when the underlying dynamics is periodic in time, but spatiotemporal structure can persist when the underlying dynamics is chaotic. We interpret this as a competition between diffusion, which makes the population densities homogeneous in space, and chaos, where sensitive dependence on initial conditions leads to different locations in space following different trajectories in time. We investigate whether this competition leads to a preferred length-scale for the spatial structure.

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PP1

Nematic Locking Principle in Active Nematics: Implications for Chaotic Self-Mixing

Active nematics are non-equilibrium fluids that consume locally available energy to generate spontaneous flow dynamics. A well-known example of active fluids is 2D dense suspensions of microtubule (MT) bundles tightly packed by kinesin motors. Powered by Adenosine Triphosphate, these bundles continuously extend, bend, and buckle. The extended structure of MT bundles appears as striation patterns in fluorescence microscopic images. The system's local orientation field, i.e., the director field, can be extracted from the striation patterns by taking the tangent to the MT bundles. These bundles fracture when the bundle curvature grows too large, creating topological defects. These mobile defects act like stirring rods, moving in a complex braiding pattern to mix the fluid. The chaotic self-mixing of the fluid can be quantified using concepts from chaos theory Lyapunov exponent and topological entropy. In this study, we investigate MT-based active nematics from the perspective of the "nematic locking" principle: a nematic contour (i.e., an integral curve of the director field) advected forward in the flow remains a nematic contour. We first provide evidence from experimental data that this principle holds for MT-based active nematics. Then, we modify the standard theoretical model for MT-based active nematics to impose the constraint of nematic locking explicitly. Finally, we explore the consequences of the nematic locking principle on the measures of chaotic self-mixing.

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PP1

Widespread Chaos Near Shilnikov-Hopf in a Model of Neural Bursting

This poster investigates the origin and onset of chaos in a mathematical model of an individual neuron, arising from the interaction between 3D fast and 2D slow dynamics. Central to the chaotic dynamics are multiple homoclinic connections and bifurcations of saddle equilibria and periodic orbits. The model reveals a rich array of codimension-2 bifurcations, including Shilnikov-Hopf, Belyakov, Bautin, and Bogdanov-Takens points, which play a pivotal role in organizing the complex bifurcation structure of the parameter space. We explore various routes to chaos occurring at the intersections of quiescent, tonic-spiking, and bursting activity regimes within this space, and provide a thorough bifurcation analysis. Despite the models high dimensionality, its fast-slow dynamics allow a reduction to a one-dimensional return map, accurately capturing the systems complex trajectory and dynamical behavior. Our approach integrates parameter continuation analysis, newly developed symbolic techniques, and Lyapunov exponents, collectively unveiling the intricate dynamical and bifurcation structures present in the system.

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PP1

Standing Wave Solutions for a Heterogeneous Reaction-Diffusion Equation

Motivated by problems in ecology, we study standing wave solutions of a reaction-diffusion equation modeling population dynamics. Central to our study is the existence of a finite favorable habitat patch, where positive growth rates for the species are attained with the remainder of the spatial domain unfavorable to species existence. Using dynamical systems methods, we investigate the existence and stability of pulse-like standing waves and explore how these solutions depend on the system parameters in an Allee-type growth model.

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PP1

Aperiodic Spectral Neural Activity in Identifying Seizure Onset Zones

Neuro-electrophysiological recordings contain prominent aperiodic activity meaning irregular activity, with no characteristic frequency, which has been variously referred to as 1/f, fractal, or scale-free activity. There are various frameworks and methods for analyzing aperiodic activity, including both time-domain and frequency-domain approaches. In this study, we introduce an algorithm to parameterize neural power spectra with a focus on aperiodic components. Our goal is to estimate information flow via directional connectivity and infer the excitation-inhibition balance, as reflected in the antagonistic information flow between SOZ and non-SOZ regions across multiple frequencies. Specifically, we examine the changes in the 1/f power slope between SOZ and non-SOZ regions from preictal to ictal phases. We validate this algorithm on a larger dataset to analyze the excitation-inhibition imbalance between SOZ and non-SOZ regions, as characterized by the 1/f power slope. By investigating the dominant information flow from non-SOZ to SOZ regions, we aim to understand how these dynamics evolve during the transition from preictal to ictal states. Additionally, we apply a machine learning algorithm to develop a predictive model for identifying the seizure onset zone and exploring its relationship with seizure outcomes. This analysis will be further validated using synthetic data to examine the dynamics of coupled oscillators.

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PP1

Bifurcation Structure of Interval Maps with Orbits Homoclinic to a Saddle-focus

We study homoclinic bifurcations in an interval map associated with a saddle-focus of (2, 1)-type in Z2-symmetric systems. Our study of this map reveals a homoclinic structure of the saddle-focus, with bifurcation unfolding guided by the codimension-two Belyakov bifurcation. We consider three parameters of the map corresponding to the saddle quantity, splitting parameter, and the focal frequency of the smooth saddle-focus in a neighborhood of homoclinic bifurcations. We symbolically encode the dynamics of the map in order to find stability windows and locate homoclinic bifurcation sets in a computationally efficient manner. The organization and possible shapes of homoclinic bifurcation curves in the parameter space are examined, taking into account the symmetry and discontinuity of the map. Sufficient conditions for stability and local symbolic constancy of the map are presented. This study provides insights into the structure of homoclinic bifurcations of the saddle-focus map, furthering comprehension of low-dimensional chaotic systems.

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PP1

Spectral Stability of Planar Periodic Vegetation Stripes on Desert Hillsides

The phenomenon of vegetation pattern formation has been observed in a variety of ecological contexts, particularly in semi-arid ecosystems. The formation of such patterns can be seen as an adaptation by the ecosystem to resource scarcity. On desert hillsides, vegetation stripes have been observed to move uphill at a constant rate, over large timescales (mm/yr), while maintaining their profile. We seek to show that these phenomena are well described by periodic traveling wave solutions to the Klausmeier reaction diffusion advection PDE, which describes interaction of water and vegetation. Our work is focused on the analysis of this model in the case of a sloped planar domain, where the advection of water dominates diffusion. We construct a family of far-from-onset traveling wave train solutions using geometric singular perturbation theory. Our aim is to show that such solutions are linearly stable to 2D perturbations using exponential trichotomies and Lin's method.

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PP1

How Advocacy Groups on Twitter and Media Coverage Can Drive U.S. Firearm Acquisition: a Causal Study

Firearm injuries are a leading cause of death in the United States. Despite significant public health risks, Americans continue to purchase numerous firearms. Known drivers of firearm acquisition include fear of violent crime, fear of mass shootings, and panic-buying. Additionally, advocacy groups' activity on social media may capitalize on emotions like fear and influence firearm acquisition. No causal framework has yet explored the simultaneous effects of these variables. We elucidate the causal roles of media coverage of firearm laws and regulations, media coverage of mass shootings, media coverage of violent crimes, and the Twitter activity of anti- and pro-regulation advocacy groups in short-term firearm acquisition in the United States. We data-mined daily time series for these variables (2012 - 2020) and employed the PCMCI+ framework to investigate the causal structures among them simultaneously. Our results indicate that the Twitter activity of anti-regulation advocacy groups directly drives firearm acquisitions. We also find that media coverage of firearm laws and regulations and media coverage of violent crimes influence firearm acquisition. Although media coverage of mass shootings and online activity of pro-regulation organizations are potential drivers of firearm acquisition, in the short term, only the lobbying efforts of anti-regulation organizations on social media and specific media coverage appear to influence individuals' decisions to purchase firearms.

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PP1

Node Degree Volatility for Seizure Onset Zone Identification

Studying the functional connectivity of evolving functional epileptic networks is a powerful approach for identifying critical nodes responsible for seizure initiation. Building on our previous work that demonstrated the utility of temporal derivatives of graph theoretic measures in critical node identification, particularly the derivative of node degree, this study enhances our criterion by developing a machine learning model trained to capture the nuanced dynamics of these network derivatives during seizures. This work also demonstrates the broader potential of temporal derivative-based network analysis as an important tool for examining dynamic properties in complex systems.

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PP1

Almost Globally Stable Consensus Control on So(4) with Ring Lattice Topologies and Feedback Reshaping

Consensus control in multi-agent systems is the control strategy that aligns the configurations of all agents which share information according to a network, defined by a communication topology. Single agent linear Lyapunov-based control laws are first formulated in terms of the configuration coordinate in the Lie group $SO(4)$, a four-dimensional compact manifold, to drive the configuration to identity with almost global asymptotic stability. This strategy is then extended to N-agent consensus control on $SO(4)^N$ with ring lattice networks using Morse-Bott-Lyapunov functions. While the base case control law proportional to the relative configurations can result in locally stable non-consensus equilibria and hence only local stability of the consensus manifold, it is shown that the use of feedback reshaping with nonlinear functions of the relative configurations results in destabilization of the nonconsensus equilibria and produces consensus with almost global asymptotic stability on $SO(4)^N$.

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PP1

On Catastrophic Turing Bifurcations

Our focus centers on pattern formation via Turing bifurcations near spatially homogenous bifurcations such as a saddle-node point or a cusp. It turns out that the standard

Ginzburg-Landau approach inadequately captures the dynamics in systems where an elementary catastrophe, like a fold or cusp bifurcation, interacts with a Turing bifurcation. To address this problem, we modified the conventional Ginzburg-Landau Ansatz, deriving new coupled systems of modulation equations that accurately describe the local dynamics. Moreover, we have demonstrated that in what we term Turing-fold, Turing-cusp, Turing-butterfly, and other catastrophic Turing bifurcations, these derived modulation equations are universal. Specifically, for any n-component PDEs in one spatial dimension in which a Turing-catastrophe bifurcation occurs, we can derive the corresponding modulation equation. Using these modulation equations, we have garnered much more insight into Turing-catastrophe bifurcations. For example, we demonstrated that when a supercritical Turing bifurcation occurs near a saddle-node bifurcation, the stable periodic orbits that emerge from the Turing bifurcation will extend beyond the tipping point. Moreover, we established the existence of small bounded Busse ballons near a homogeneous pitchfork bifurcation.

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PP1

Pattern Formation in Biological Membranes: Travelling Waves in the Min System

Recently, bulk-surface models have been derived to study the dynamics of cell proliferation for the MIN protein system, in particular when exposed to advection in the cell interior. We study travelling wave bifurcations in a reduced bulk integrated model, which forms a spatially one-dimensional reaction-diffusion-advection system with six components. Due to the conservation laws innate to the MIN system, a complex and fascinating combination of conservative Turing-Hopf- and Eckhaus-type instabilities can be observed. The model background stems from E. coli bacteria, where the MIN protein system plays an important part in localizing the cell center during cell division. It consists of the MinC, MinD and MinE proteins, whose chemical interactions lead to oscillations of MinD and MinE along the cell. These oscillations induce a time-average gradient that initializes cell division. Similar mechanisms have been observed or suspected in other bacteria [Feddersen et al., Dynamics of the Bacillus subtilis Min System, mbio 2021]. The model we study was proposed in [Meindlhumer et al., Directing Min protein patterns with advective bulk flow, nature communications, 2023]. This is joint work with Jens Rademacher (University of Hamburg).

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PP1

Trajectory-Based Study and Visualization of Coherent Flow Structures in Chemical Reactors

The analysis of fluid transport and mixing in chemical reactors is crucial to avoid dead zones and control concentration distributions. From a Lagrangian perspective, coherent flow structures are key. Recent computational methods can identify finite-time coherent sets directly from fluid particle trajectories obtained from numerical simulations or laboratory experiments such as 4D-PTV or Lagrangian sensors. This contribution demonstrates the application of trajectory-based approaches to identify coherent flow structures in chemical reactors and analyze their transport properties. Several recently proposed methods, such as spectral clustering of trajectories or single trajectory diagnostics, have been implemented in Python to improve performance and ease embedding. In particular, we identify vortical flow structures that appear to interconnect large scale coherent recirculation zones. We study their lifetimes and their role in the global material transport.

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PP1

Fault Estimation-Based Security Control for Periodic Piecewise Cyber Physical System under Intermediate Estimator Approach

This work addresses the issue of fault estimation for periodic piecewise cyberphysical systems in the presence of cyberattacks and external disturbances. Specifically, the periodic piecewise intermediate estimator is configured to estimate the faults. Herein, the estimator provides a more precise estimation of the faults than the existing ones due to the periodic piecewise nature. A fault-tolerant security control protocol is developed by leveraging the information provided by this estimator. Precisely, the control protocol is carefully crafted to tolerate the impact of the faults and attacks on the system's dynamics, ensuring that the system's intended performance is achieved despite malicious factors. Furthermore, the stability conditions to affirm the stability of the undertaken systems are established in the frame of linear matrix inequalities by using Lyapunov stability theory and integral inequalities. Subsequently, the precise design of the developed controller and estimator is generated by solving the established stability criteria. Eventually, the simulation results, which include application-orientated ones, are offered to certify the efficiency of the proposed developed results. This work offers a significant contribution to the field of secure control in cyber-physical systems with periodic piecewise nature, providing practical tools for enhancing system resilience in the face of complex, real-world challenges.

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PP1

Cellular and Parkinsonian Network Dynamics in a Conductance-Based Model of the Pedunculopontine Nucleus in Rodents

The motor pathways between the basal ganglia (BG) and the brainstem are crucial to the development of Parkinsons Disease (PD) and its treatment. Recent experiments suggested that long-term motor recovery in dopamine-depleted rodents could result from repeated stimulation of specific BG sites, and the pedunculopontine nucleus (PPN) is necessary for motor rescue. The role of the PPN has mostly been overlooked in computational work on Parkinsonian brain dynamics. We developed a novel conductance-based model of neurons in the PPN receiving inputs from the substantia nigra pars reticulata (SNr), the BG output nucleus. We leverage patch-clamp data to ensure our PPN model, consisting of a system of nonlinear ODEs, reproduces the diverse activity patterns to various forcing signals observed within this nucleus. PPN neurons have high-voltage activated calcium channels, and we use bifurcation analysis to investigate their contributions to high-frequency oscillations. We explain how neuronal firing saturates with increasingly large applied currents. In addition to analyzing these model neurons in isolation, we consider the dynamics of the network formed by coupling glutamatergic PPN neurons with model SNr neurons. The novel step of building a conductance-based model of the PPN presents an opportunity to advance our understanding of these neurons on a cellular-level as well as the contributions of this brainstem nucleus in PD treatment on a network-level.

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PP1

Modeling Coupled Online and Offline Dynamics of Protesting Activity on Networks

The expansion of social media has enabled an increasing portion of the global population to access diverse information and share opinions online. However, this convenient medium can sometimes become a hotbed for conflict and tension. Research indicates that online tension can trigger offline social movements, while physical protests, in turn, can intensify online engagement. Our work extends mathematical modeling of the spatiotemporal dynamics of social protest activity by incorporating the coupled effects of online engagement and offline protests. Specifically, we introduce a network model with two layers: an online layer for social media engagement that evolves on a social network, and an offline layer for physical protesting activities. Based on findings of bidirectional causality between online activity and offline protests, we assume that a segment of the online-engaged population may participate in offline protests, while tensions from physical uprisings can amplify online engagement. Using mean-field approximations, we develop ODE models on networks that align well with stochastic simulations while achieving faster simulation speeds. These models enable us to analyze online-offline dynamics across various network types, predict the scale of offline activities, and connect with real-world data.

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PP1

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

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.

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PP1

A Minimal Model for Rem Sleep Without Atonia

One of the characteristics of REM sleep is atonia, or muscle paralysis due to the inhibition of motoneurons in the spinal cord. A role of atonia is to prevent one from acting out dreams during REM sleep, which could cause inadvertent harm to the individual or those around them. REM active neurons, which are part of the sleep-wake circuitry, project via two pathways to the spinal cord motoneurons which control atonia. Damage to the ventral sublaterodorsal nucleus (vSLD) or ventral medial medulla (VMM), which are key elements of these pathways, may result in an individual experiencing REM sleep without atonia. We construct a firing rate model that combines the sleep-wake cycle and atonia pathways to discern the roles of vSLD and VMM on network dynamics. By functionally disabling key pathways in the atonia circuit, using phase plane analysis and numerical simulations, we suggest various explanations that may underlie REM sleep without atonia.

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PP1

Real-World Data-Driven Modeling for Chaotic Circuits and Nonlinear Elements

We show data-driven modeling techniques for experimentally measured chaotic circuits and nonlinear elements such as laser diodes by extracting differential equation models from real-world data. This work aims to validate data-driven models from algorithms like Sparse Identification of Nonlinear Dynamics (SINDy) when applied to chaotic systems and nonlinear circuit elements, particularly those enabling high-power lasers. Importantly, we demonstrate that despite favorable SINDy results for simulated chaotic Lorenz systems; electronic hardware implementations challenge the algorithm and result in new systems of equations that are Lorenz-like. Here, we consider two means of quantifying these differences. First, we dissect Lorenz waveforms into information primitives such as basis functions. Next, we consider recent advances in the evaluation of reservoir computers involving statistics of Lorenz waveforms. These efforts serve as first steps to extracting models for nonlinear circuit elements, which can be elusive due to imperfections in real-world systems. In fact, some models are narrow, intractable, or even unknown. For example, the real-world behavior of high-power laser diode bars is rich with non-idealities. As a result, these elements promote a strong need for validated, data-driven models since their ideal, individual, and ensemble behaviors all preclude simple modeling.

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PP1

On the Application of Machine Learning to Steady-State Incompressible Fluid Within a Cavity with Entropy Prediction.

Addressing fluid dynamics in complex systems poses significant computational challenges. Traditional computational fluid dynamics (CFD) methods (e.g finite element, finite volume, and other decomposition methods) are powerful yet can require substantial computational resources and may struggle with rapid parameter variations or inverse problem-solving. CFD's applications span across various fields, enhancing both technological advancements and practical implementations. The application of machine learning (ML) techniques to computational fluid dynamics (CFD), specifically in predicting steady-state behavior of incompressible fluids within complex geometries, represents a significant shift from traditional methods. This research introduces a novel ML framework specifically tailored to respect the foundational principles of fluid mechanics, thereby addressing these computational challenges. By integrating ML with established fluid dynamics laws, this framework aims to enhance the accuracy and efficiency of entropy predictions and engineering fluid properties in steady-state conditions. Results indicate that this approach not only reduces computational demands but also improves prediction accuracy, offering a promising new direction for advanced CFD methodologies.

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PP1

Bridging Random Dynamics: Random Generalized Differential Equations and Their Applications

The theory of random dynamical systems (RDS) is a cornerstone in applied mathematics, with wide-ranging applications in biology, engineering, and the modeling of random ordinary differential equations (ODEs). Building upon this well-established framework, we introduce random generalized differential equations (random generalized ODEs), extending the classical theory of generalized differential equations to encompass random dynamics. This framework provides a unified approach to studying diverse random systems influenced by noise, time delays, and impulsive effects. We establish conditions for the existence and uniqueness of solutions to random generalized ODEs, tailored to address the intrinsic complexities of randomness. These conditions deviate from traditional deterministic analogs. Moreover, we present the proof of a multivalued cocycle generated by families of random generalized ODEs, offering a foundational result with far-reaching implications.

This multivalued cocycle framework bridges the gap between different types of non-autonomous random differential equations, including random Volterra-Stieltjes equations, random impulsive differential equations, and random delay differential equations. These contributions advance the theoretical foundations of RDS while highlighting the versatility and applicability of random generalized ODEs as a tool for studying complex behaviors in random environments.

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PP1

Pattern Formation in Ecosystems

Self-organized vegetation patterns, such as stripes, spots or rings (fairy circles), are frequently observed in ecosystems prone to tipping. We consider two-component reaction-diffusion models to study pattern formation, driven by scale-dependent feedbacks that naturally arise in ecosystem models, as ecological processes often occur on different (spatial) scales. Such a separation of scales allows for a decomposition in long- and short-range dynamics ('slow and 'fast), that can be studied using geometric singular perturbation theory (GSPT). We study singular patterns in an explicit model for the autotoxic interaction between seagrass and hydrogen sulfide in the soil, however similar vegetation patterns have been studied in dryland ecosystem models. We show the existence of stationary front- and pulse-like solutions in one spatial dimension. Fast jumps between slow invariant manifolds allow for sharp transitions between bare soil and vegetation, matching observations of patterns in seagrass meadows. Using the same geometric approach, a plethora of additional singular patterns can be constructed (e.g., traveling, periodic patterns). Furthermore, the slow-fast approach also forms the foundation of the stability analysis of these singular patterns. In ongoing research, we consider the effects of bounded domains and of (localized) spatial heterogeneities on the established existence and stability results.

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PP1

Reaction-Diffusion Systems on Cubic Superlattices

Pattern formation in two-dimensional reaction-diffusion systems has long been studied using group theoretic means. In addition to patterns on the square and hexagonal lattices, superlattice structures have also been found, belonging to normal form systems of higher dimension. In three dimensions the systems with the periodicity of the simple cubic, fcc, and bcc lattices have also been examined, but there are three more superlattices that require study: two with normal forms of 24 dimensions and one of 48 dimensions. We find the solutions for these systems, their branching equations and stabilities. We also make explicit predictions for the Brusselator model.

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PP1

Topological Structure of the Cyclonic-Anticyclonic Interactions in Sea-Level Pressure Fields in the North Atlantic

Understanding the interaction between cyclones and anticyclones is useful to understand the atmospheric dynamics that generates weather patterns in the North Atlantic region. Cyclones are associated with low-pressure systems, and anticyclones, associated with high-pressure systems. The interaction can affect storm formation, intensity, and distribution. Topological Data Analysis (TDA) is a field within applied mathematics that uses concepts from algebraic topology to extract topological information from data. Persistent homology is one of the tools in TDA which gives a topological summary of the data. We used persistent homology to obtain a topological summary of the following dynamics: a cyclonic system is surrounded by anticyclones and vice versa. We generate this topological summary for each day of years between 1948 and 2023. Our initial analysis reveals different patterns of activity for different seasons among both interactions. There is a change in the overall interaction from the past to the future, pointing to climate change. We also correlate this with the Atlantic Multidecadal Oscillation and whether this interaction has some similar oscillation.

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PP1

Iterative Kernel Analog Forecasting

Data-driven methods are becoming increasingly widespread in all spheres of life. This is primarily because of two factors availability of good-quality data and advancements in the computational capabilities. One such method was introduced by Zhao and Giannakis in

2016 called the Kernel Analog Forecasting (KAF). As the name suggests, it is a kernel method for non-parametric statistical forecasting of measure-preserving and ergodic dynamical systems. A basic assumption of this method is that it requires the data to be sampled at the constant time. When running a simulation study, this is an easy assumption to control whereas while working with real data, it is often the case that the time-steps are not constant. We propose a new method which can handle gaps in the data. In this work, we delve into the case with a non-constant time-step, however, the timestamps are linear to each other, that is, we only have a subsequence of the full data. We call this method, Iterative Kernel Analog Forecasting (IKAF). The convergence of KAF depends on the Birkhoff theorem and likewise, there exists a subsequential Birkhoff theorem which implies the convergence of certain good subsequences. A detailed description of this new method, along with the behaviour of the root mean square error will be presented.

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PP1

Homogenization of Non-Divergence Type Equation with Oscillating Coefficients Defined on a Highly Oscillating Obstacles

We discuss the homogenization of a highly oscillating obstacle problem using the viscosity method. The equation we deal with is a non-divergence type equation with oscillating coefficients. To analyze the behavior of solutions in the obstacle problem, we construct a corrector function, periodic function when the obstacle is given as 1. By utilizing this corrector, we identify the so-called "strange term behavior" when the size of the domain where the obstacle is defined reaches a critical value. We then modify the corrector for critical size and analyze the solution's behavior when the size of the obstacle is either larger or smaller than the critical value.

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PP1

Oseledets Subspace Score-Based Generative Models.

Given samples from a target probability distribution, score-based generative models aim to produce more samples from the target by learning "scores' or gradient log densities of some intermediate probability distributions. These distributions are pushforwards through a deterministic or stochastic process on sample space, starting at the given target samples. Here we analyze the evolution of the score function along such sample paths with the ultimate goal of reducing their dimension. Specifically, we investigate the projections of the score evolutions along cotangent subspaces obtained via the Oseledets multiplicative ergodic theorem for random linear cocycles. Our decomposition of the score evolutions along Oseledets spaces exposes a simpler dynamical system for scores orthogonal to the data manifold. Moreover, the spaces can be computed numerically along sample paths, suggesting new alternatives for manifold learning that leverage the dynamics of existing generative models. Finally, we seek to derive new generative models on the computed lower-dimensional data manifolds that have bounded scores for all time.

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