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IP1
Animal Behaviors in Response to Fluid Instabilities

Biological organisms have presumably adapted their behaviors or features in response to surrounding mechanical forces or instabilities to achieve better performance. In this talk, I will discuss three problems in which the dynamical system approach elucidates the physics behind animal behaviors. First, we investigated how cats and dogs transport water into the mouth using an inertia-driven (lapping) mechanism. We found that to maximize water intake per lap, both cats and dogs close the jaw at the column break-up time governed by unsteady inertia. This break-up (or pinch-off) time can be predicted using the stability analysis of the water column in which surface tension balances with inertia. Second, we studied how animals plunge-dive and survive from impact. Physical experiments using an elastic beam as a model for the body attached to different shapes revealed limits for the stability of the injuries during plunge-dive. The body response can be simplified as the Euler beam buckling problem with unsteady impact force on the diving front. Finally, I will discuss the mechanism of releasing water lodged in the ear canal. For example, people often shake their head sideways to remove water out of ear canal after swimming or showering. This removal process involves high acceleration to push water out of a canal, which is analogous to the Rayleigh-Taylor instability.

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IP2
Determining Spectral Stability via the Maslov Index and Conjugate Points

Being able to determine the spectral stability of stationary solutions is an important step towards understanding the long-time behavior of PDEs that describe a variety of physical and biological processes. For systems whose evolution respects certain symplectic structures, spectral stability can be understood through the use of a topological invariant know as the Maslov index and the counting of what are called conjugate points. In this talk, these structures and tools will be defined and described, and recent related results will be presented that allow one to efficiently and rigorously determine spectral stability via validated numerics for reaction-diffusion systems with gradient nonlinearity and for the Swift-Hohenberg equation.

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IP3
Using Dynamical Systems Tools to Incorporate Diverse Sensing into Models of Collective Motion

In the literature on modeling animal group motion, existing work can neglect to explicitly define how individuals sense the world. As a result, these models may implicitly encode sensing features that are similar to vision, which is often relied on by humans. While these models are well studied, they may not be able to capture interactions between animals whose sensing is qualitatively different from those used by humans. For example, animals which use active senses in which signals are generated and may be intercepted, like echolocation, have the potential to interact with each other through the sensing signals they produce. One would expect then that animals which use diverse types of sensing may show different patterns of collective behavior than those using exclusively vision-based interactions. We can use tools from data-driven dynamical systems to help us uncover if collective motion results from different types of sensing and interactions, and to move towards identifying the rules underlying such motion when it occurs. In this talk, we will explore this problem to better understand how to model the motion of wild bat swarms from field experiments.

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IP4
The Remarkable Accuracy of a Pendulum Clock

Hugh Hunt is the Keeper of the Clock at Trinity College Cambridge. It is a remarkable mechanical instrument, 113 years old and still capable of keeping time to within one second per month - that's an accuracy better than 1 part per million, and much better than any quartz watch. So what is the secret of its accuracy? It is after all just a pendulum. The story will be told with data live streamed from the clock in Cambridge. If you want a sneak preview of the latest data then take a look at clock.trin.cam.ac.uk . Many of you will know the basics of timekeeping, certainly that the period of a pendulum is very stable. But perhaps 300 years ago it was well known that the period of a pendulum depends on its amplitude of swing, on temperature and barometric pressure and on other environmental factors like wind, snow and pigeons. In the early 1800s the extraordinary "double three-legged gravity escapement" was invented by Sir George Biddell Airy, the then Astronomer Royal, and Edmund Beckett Denison (Lord Grimthorpe). They installed a clock in the Houses of Parliament at Westmister known by the name of its bell "Big Ben". The new clock incorporated this revolutionary gravity escapement. It transformed the accuracy of tower clocks. The Trinity clock was built in 1910 as a bequest from the then Lord Grimthorpe. It is perhaps the most accurate clock of its type ever built. The talk will describe how the clock is wound and regulated and what happens if the clock stops (usually because someone forgets to do the winding) But the fun bit is all the instrumentation that now peppers the clock. Six raspberry pi computers measure just about everything you might want to measure using lasers, spirit levels, microphones and GPS satellite data. One of the greatest discoveries of the past few years is how sunshine affects the clock. Its not just temperature, its the radiant heat of the sun that matters. One of the best kept secrets is exactly when it is best to run "The Great Court Run" made famous from the film Chariots of Fire. That's all been measured with great accuracy too. Just when you thought that the constant period of a pendulum was all that matters, well think again!

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IP5
Modeling Complex Oscillations in Pancreatic Beta Cells: A History of Successes, A Future of Challenges

This year marks the fortieth anniversary of the model introduced by Theresa Chay and Joel Keizer for bursting oscillations in pancreatic beta cells. One key early advance was an explanation of how those cells transduce plasma glucose concentrations via their internal rate of glucose metabolism into an appropriate level of insulin secretion. This has advanced the study of diabetes, which results when the beta cells are unable to secrete enough insulin to maintain glucose in the normal range. The model has also had a profound influence on the theory of dynamical systems, as a paradigmatic example of one form of bursting and a stimulus for the development of a general classification of possible bursting patterns. The model has gone through major renovation and elaboration as an array of oscillatory patterns on time scales ranging from seconds to minutes and their modulation by key hormonal and neuronal signals have been incorporated. This history of success has been made possible by tight coordination of modeling with experimentation through an iterative process of generating and testing predictions. Today, the model faces new challenges from new data and new concepts, including the balance between influx of calcium from outside the cells and release of calcium from internal stores, as well as the balance between glucose metabolism in cytosolic anaerobic glycolysis and mitochondrial aerobic respiration.

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IP6

A Journey Through the Use of Mathematical Models to Gain Insight into Ecological and Sociological Phenomena

While mathematical models have classically been used in the study of physics and engineering, recently, they have become important tools in other fields such as biology, ecology, and sociology. In this talk I will discuss the use of partial differential equations and dynamical systems to shed light onto social and ecological phenomena. In the first part of this talk, we will focus on an Ecological application. For an efficient wildlife management plan, it is important that we understand (1) why animals move as they do and (2) what movement strategies are robust. I will discuss how reaction-advection-diffusion models can help us shed light into these two issues. The second part of the talk will focus on social applications. I will present a few models in the study of gentrification, urban crime, and protesting activity and discuss how theoretical and numerical analysis have provided intuition into these different social phenomena. Moreover, I will also point out the many benefits of utilizing a mathematical framework when data is not available.

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IP7

Linear Response Theory, Koopmanism, and Optimal Fingerprinting Methods for Climate Change

Detection and attribution studies have played a major role in shaping contemporary climate science and have provided key motivations supporting global climate policy negotiations. The goal of such studies is to associate observed climatic patterns of climate change with acting forcings - both anthropogenic and natural ones - with the goal of making statements on the acting drivers of climate change. In most cases, detection and attribution techniques are based on the concept of Pearl causality: one investigates the changes in a system following the adoption of alternative courses of action. The statistical inference is usually performed using regression methods referred to as optimal fingerprinting. We show here how a fairly general formulation of linear response theory relevant for nonequilibrium systems provides the physical and mathematical foundations behind the optimal fingerprinting method. Our angle, which also takes advantage the Koopman operator framework, allows one to clearly frame assumptions, strengths and potential pitfalls of the method, and relate the effectiveness of detection and attribution to model error, to the acting climatic feedbacks, and to the proximity to tipping points. The take-home message is that, by and large, detection and attribution is based upon a solid framework but one should re-examine classical notions of natural variability by considering the concept of snapshot/pullback attractor.

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IP8

Mathematical Modeling and Simulation of Multi-scale Yeast Prion Aggregate Dynamics

Prions are responsible for a variety of irreversible neurodegenerative diseases (Creutzfeldt-Jakob disease in humans and mad-cow disease in cattle). Central to these biological outcomes is the unique ability of the prion protein to assemble into self-templating, transmissible aggregates. While prion disease is fatal to mammals, in yeast a host of harmless prion phenotypes have been identified. Moreover, mild experimental manipulations can fully reverse prion phenotypes in yeast. As such, yeast are ideal for studying prion aggregate dynamics to uncover mechanistic insight into their stability. However, most mathematical approaches focus on the protein dynamics alone in isolation of living (and dividing) cells and have failed to recapitulate in vivo properties of yeast prion strains. My group develops multi-scale mathematical models of both prion aggregates and yeast cells. I will present several results building up multiple scales of the yeast prion system. First, by considering a stochastic model of prion amplification, we uncover a structural difference between prion strains. Then, we link protein and cellular scales by developing a multi-scale aggregate and generation structured population model to determine in vivo prion amplification rates. Finally, we study the spatial heterogeneity of yeast colonies by coupling a center-based model of a growing colony with intracellular aggregate dynamics.

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IP9

Exotic Patterns in Faraday Waves

A standing wave pattern appears on the free surface of a fluid layer when it is subjected to vertical oscillation of sufficiently high amplitude. Like Taylor-Couette flow (TC) and Rayleigh-Benard convection (RB), the Faraday instability is one of the archetypical pattern-forming systems. Unlike TC and RB, the wavelength is controlled by the forcing frequency rather than by the fluid depth, making it easy to destabilize multiple wavelengths everywhere simultaneously. Starting in the 1990s, experimental realizations using this technique produced fascinating phenomena such as quasipatterns and superlattices. This sparked a renaissance of interest in Faraday waves, which led to new mathematical theories of pattern formation. However, the Faraday instability has been the subject of surprisingly little numerical study, lagging behind TC and RB by several decades. We will discuss some of the exotic patterns found in recent numerical simulations. The first 3D simulation reproduced hexagonal standing waves, which were succeeded by recurrent alternation between quasi-hexagonal and beaded striped patterns, interconnected by spatio-temporal symmetries. In a large domain, a pattern of square waves divides spontaneously into four subsquares with synchronized diagonal blocks or else can undergo a twisted sheared secondary instability. A liquid drop subjected to an oscillatory radial force comprises a spherical version of the Faraday instability. Simulations show Platonic solids alternating with their duals while precessing.

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SP1

Juergen Moser Lecture - Exploring the World of Coupled Oscillators

This talk begins with a retrospect back to half a century ago when I changed the research field to nonlinear dynamics. The earliest target of my study was the oscillating Belousov-Zhabotinsky reaction. In an effort of mathematically understanding how its wave patterns emerged, a small amplitude equation, now called the complex Ginzburg-Landau equation, was derived from a hypothetical reaction-diffusion model. This work was important to the subsequent research career of my own, particularly because both the so-called Kuramoto-Sivashinsky equation and Kuramoto model originated from the CGL and its variant through dynamical reduction. Some background of the birth of these model equations is reviewed. Practical and conceptual significance of the two reduction schemes developed for coupled oscillators is also discussed. The principal role of dynamical reduction in general is to provide a rough sketch of the reality. Still it could serve as a reliable guide indicating in which way to move on when we get lost in the complexity of the real world. Indeed, the analysis of the reduced oscillator models has contributed and will contribute largely to a better understanding and control of oscillator dynamics and also to predicting new types of dynamics to be exhibited by the real oscillators.

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CP1

Patterns of Turbulence

Turbulence in wall-bounded shear flows exhibits a remarkable phenomenon: spatially periodic patterns of alternating turbulent and laminar flow emerge spontaneously from uniform turbulence as the Reynolds number is decreased. These patterns are ubiquitous in subcritical shear flows and explaining them has been a long-standing challenge for understanding the route to turbulence. From a dynamical systems viewpoint, these patterns are fascinating because they appear in a highly fluctuating, highly nonlinear state. Here we report on a model obtained from projecting the Navier-Stokes equations onto a few vertical modes, with closure coming from modelling Reynolds stresses and dissipation. The resulting two-dimensional PDE model is expressed in 4 fields describing the large-scale flow, and 1 or 2 fields describing the turbulent kinetic energy. The model can be viewed as a generalized and more fully justified version of the Barkley model for pipe flow. The model captures the transition to periodic turbulent-laminar patterns, as well as other spatiotemporal dynamics found in transitional turbulence.

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CP1

Global Instability and Nonlinear Dynamics of Finite-Reynolds-Number Flow in Compliant Rectangular Channels

Experiments have shown that flow in a compliant microchannel can become unstable at a much lower Reynolds number than flow in a rigid channel. Previous studies mainly focused on the local instability induced by fluid–structure interaction (FSI). On the other hand, we derived a one-dimensional (1D) model to study the FSI's effect on global instability [1] X. Wang, I.C. Christov, Reduced modelling and global instability of finite-Reynolds-number flow in compliant rectangular channels, Journal of Fluid Mechanics 950 (2022) A26, doi:10.1017/jfm.2022.802; preprint arXiv:2202.11704]. The critical Reynolds numbers predicted, beyond which the inflated base state of the 1D FSI model is linearly unstable to streamwise perturbations, are in agreement with experiments. The unstable modes have frequencies close to the natural frequency of the elastic wall, suggesting that the observed instabilities are a resonance phenomenon. Using direct numerical simulations of our 1D reduced-order FSI model, we demonstrate that self-sustained oscillations are triggered during the start-up flow in an initially undeformed channel. Our modeling, simulation, and stability framework can be applied to any microfluidic system with similar geometric scale separation [2] I.C. Christov, Soft hydraulics: from Newtonian to complex fluid flows through compliant conduits, Journal of Physics: Condensed Matter 34 (2022) 063001, doi:10.1088/1361-648X/ac327d; preprint arXiv:2106.07164].

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CP1

Numerical Continuation of a Localized State in Sheared Annular Electroconvection

We investigate a flow that resembles a rotating wave with a single, isolated vortex that occurs in sheared annular electroconvection. We use numerical bifurcation methods based on time-integration to investigate the origins of the flow and its stability. We study a model that simulates the flow of a liquid crystal film in the Smectic A phase suspended between two annular electrodes, and subjected to an electric potential difference and a radial shear. Due to the Smectic A nature of the liquid crystal, the fluid can be considered two-dimensional and is modelled using the 2-D incompressible Navier-Stokes equations coupled with an equation for charge continuity. A Newton-Krylov method is implemented for the continuation of solutions and the identification of the flow transitions that result due to changes in the model parameters.

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CP1

Exploring the Geometry of Chaotic Convection

Using large-scale computing resources and efficient parallel algorithms it is now possible to numerically simulate chaotic fluid motion in large domains and for experimental conditions. Powerful ideas from dynamical systems theory, including covariant Lyapunov vectors (CLVs) and exact coherent structures (ECS), have been used in different settings to provide exciting new insights into the chaotic dynamics of high-dimensional systems. However, the dimension of most laboratory-scale fluid systems is expected to be extremely large making a computational study using the CLVs and ECS computationally expensive. However, Rayleigh-Benard convection (a shallow fluid layer heated from below) provides a tractable fluid problem where fundamental new insights using these ideas from dynamics systems theory are now possible. We discuss our exploration of chaotic convection in a small periodic box with an aspect ratio on the order of ten. We describe our efforts to compute the CLVs and ECS for chaotic convection in this domain. The CLVs provide a description of the tangent space and the ECS quantifies the state space. We are particularly interested in how these two descriptions can be used together to provide fundamental new insights into the geometry of high-dimensional chaotic dynamics in the state space and tangent space. Supported by NSF CBET-2151389

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CP1

On the Non-Linear Instability of the Burgers Vortex

Burgers' vortex is one of the few analytically known, three-dimensional, vortical solutions to the Navier-Stokes equation. It relies on vortex stretching, thought to be one of the sustaining mechanisms of turbulence. Surprisingly, this solution was shown to be linearly stable. At the same time, there are theoretical indications that families of less symmetric equilibria exist near Burgers' solution. We explore the phase space around Burgers flow by direct numerical simulations of finite-sized perturbations for low and intermediate Reynolds numbers, relying on the finite element code OOMPHlib for time-stepping as well as the computation and continuation of equilibria and their spectra.

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CP2

A Set-Oriented Landmark Selection Scheme for Manifold Learning Techniques

In order to utilize manifold learning techniques such as Isomap and Diffusion Maps, the set of interest has to be discretized resulting in a point cloud. However, typically the number of such data points is too large such that manifold learning techniques, that are for instance based on spectral decomposition, are infeasible. This is why, one aims at finding a smaller number of so-called landmarks that still discretize the set of interest sufficiently well, applies the manifold learning technique only to those specific landmarks and uses Nystroem extension for out-of-sample points. In this work a novel set-oriented landmark selection scheme which is inspired by 3d point cloud simplification methods is presented. Given an initial point cloud approximating the set of interest, the points are iteratively moved away from each other according to a repelling force that decays linearly with distance and becomes zero at a fixed radius $r > 0$. If during this procedure a point leaves the set, it is projected back onto it. In the end, we obtain a point cloud such that the pairwise intersection of r-balls around these points is (close to) empty. This scheme is then not only applied to toy examples such as the Swiss Roll but also to attractors and invariant manifolds of (infinite-dimensional) dynamical systems which allows the identification of their intrinsic coordinates. In particular, the intrinsic geometry of the unstable manifold of the Kuramto-Sivashinsky equation is revealed.

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CP2

Reinforcement Learning-Based Estimation for Partial Differential Equations

In systems governed by nonlinear partial differential equations such as fluid flows, the design of state estimators such as Kalman filters relies on a reduced-order model (ROM) that projects the original high-dimensional dynamics onto a computationally tractable low-dimensional space. However, ROMs are prone to large errors, which negatively affects the performance of the estimator. Here, we introduce the reinforcement learning reduced-order estimator (RL-ROE), a ROM-based estimator in which the correction term that takes in the measurements is given by a nonlinear policy trained through reinforcement learning. The nonlinearity of the policy enables the RL-ROE to compensate efficiently for errors of the ROM, while still taking advantage of the imperfect knowledge of the dynamics. Using examples involving the Burgers and Navier-Stokes equations, we show that in the limit of very few sensors, the trained RL-ROE outperforms a Kalman filter designed using the same ROM. Moreover, it yields accurate high-dimensional state estimates for reference trajectories corresponding to various physical parameter values, without direct knowledge of the latter.

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CP2

Numerical Solution of DAEs and PDEs Using Physics-Informed Random Projection Machine Learning

We address a new numerical methodology based on physics-informed machine learning, based on random projections for the solution of nonlinear stiff problems of ODEs, index-1 DAEs, and PDEs. The internal weights are fixed to ones while the unknown weights between the hidden and output layer are computed with Newton's iterations and sparse QR decomposition with regularization for large scale systems. Building on previous works on random projections, we also demonstrate the numerical stability and approximation accuracy of the scheme. To deal with stiffness and sharp gradients, we propose an adaptive step-size scheme, and borrowing ideas from the bifurcation analysis toolkit, we address a continuation method for providing good initial guesses of the weights of the networks to facilitate convergence upon iterations. For our illustrations, we apply the proposed framework for the numerical solution of six benchmark problems of ODEs and index-1 DAEs, and three PDEs including the Allen-Cahn, the viscous Burgers and the KuramotoSivashinsky. We assess and compare its performance against established stiff ODEs/DAEs solvers, finite differences, Galerkin finite elements and spectral methods, thus showing that the proposed approach outperforms in several cases, traditional numerical methods in terms of both numerical accuracy and importantly computational cost.

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CP2

Prediction of Rate-Induced Tipping Phenomena Using Machine Learning

Rapid parameter variation in multi-stable dynamical systems can cause rate-induced tipping (R-tipping) phenomena. Their prediction and control are of practical importance because any multi-stable systems, which are ubiquitously found in the real-world, can in principle exhibit such tipping, However, R-tipping phenomena involve nonlinear transient behavior and changes in basin boundaries, which are in themselves difficult to address quantitatively. Reservoir computing (RC) is a rapidly developing machine learning paradigm which provides simple but powerful nonlinear time-series prediction methods. Recently, a variant of RCs, called parameter-aware RCs [L.-W. Kong et al., Machine learning prediction of critical transition and system collapse, Phys. Rev. Research, 2021], has shown their capacity to reproduce nonlinear transients and shape changes in basin boundaries. In this research, we develop a kind of parameter-aware RCs in order to predict R-tipping phenomena. The method is illustrated using numerical examples.

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CP2

Physics-Informed Machine Learning for Autonomous Manipulation in Robotics

Autonomous manipulation (AM) is a type of robotic manipulation where robotic actions such as grasping, manipulating, or moving objects is done automatically by software requiring minimal human intervention. AM is challenging and no current methods achieve anything like human-like manipulation in unstructured environments. Various machine learning approaches have shown promise in solving challenges related to AM including physics-informed neural networks (PINNs) where real-world data is learned and interpolated in a way that is consistent with physical laws. In this talk we present a novel PINNs framework for AM based on classical Euler-Lagrange rigid-body dynamics. The utility of this framework is demonstrated on various primitive robotic manipulation problems such as pushing, pulling, and rotating.

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CP2

Bayesian Nonparametric Learning of Stochastic Differential Equations

In this talk we introduce a systematic approach to learning the entire drift function of a stochastic differential equation from high-frequency data. This differs from the parametric estimation problem, where the functional or parametric form of the drift function is assumed to be known barring a finite-dimensional parameter. Towards this end, we develop learning methods that merge optimization theory in RKHS with Bayesian techniques. Importantly, our Bayesian hierarchical framework incorporates low-cost sparse learning through proper use of shrinkage priors while allowing proper quantification of uncertainty through posterior distributions. Several examples at the end illustrate the accuracy of our learning scheme.

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CP3

Simulating Coupled Phase Oscillators When Ott-Antonsen Is Not Applicable: a Moment-Based Approach

A wide variety of natural and man-made systems can be described as populations of coupled oscillators. In addition, if the coupling among units is weak, solely the oscillators phase is needed to capture the dynamics, yielding models of coupled phase oscillators. In such models, to obtain useful theoretical and phenomenological results, the infinite-size limit is usually considered. Although mathematically convenient, in practice, this limit is only fully accessible if Ott-Antonsen theory can be applied. In other cases, simulating the system can be computationally costly given the large number of variables. In this talk, we present a moment-based scheme that provides an efficient numerical simulation of a heterogeneous population of phase oscillators in the infinite-size limit. The analysis is particularized to normally distributed frequencies, giving rise to a Fourier-Hermite modes scheme. The validity and accuracy of the method is analyzed in the Kuramoto model. Then, the usefulness of the technique is established by applying it to the "Enlarged Kuramoto model", an extension of the Kuramoto model including non-pairwise and second harmonic interactions. There, the use of Fourier-Hermite modes is crucial to discern the complex transition to synchrony and to confirm the existence of collective chaos.

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CP3

Dynamics and Synchronization in Random Networks of Coupled Phase-Oscillators: A Graphon Approach

Networks of coupled phase-oscillators can be used to model a broad array of applications including circadian rhythms, flashing fireflies, and high voltage electric grids. In many of these applications, it is important to understand the long term dynamics of these oscillators on large and random graphs. We seek to shed light on this behavior by considering W-random networks (i.e., random networks generated from a graphon model). To this end, we consider a continuous dynamical system describing an infinite number of coupled phase-oscillators interacting over the graphon model, as introduced in work by Medvedev et. al. As a first main contribution, we show that, with high probability, the solution to the coupled dynamical system over a W-random network of size n converges to the solution of the continuous graphon system as $n \to \infty$ in the L_∞ norm. This result provides a novel framework for studying synchronization properties in networks of coupled phase-oscillators. To illustrate the advantages of such a graphon approach, as a second main contribution, we leverage our convergence result to study synchronization in interacting and identical Kuramoto oscillators on random graphs. In particular, suppose α_n is a function with asymptotic decay strictly slower than $\log(n)/n$. We show that the Kuramoto model on the ErdosRnyi graph, $G(n, \alpha_n)$, is globally synchronizing with high probability as n goes to infinity.

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CP3

Design of Planar Limit-Cycle Oscillators with Given Orbits and Phase-Response Properties

We propose a method for designing two-dimensional limit cycle oscillators with prescribed periodic orbits and phase response properties based on the phase reduction theory for analyzing synchronization dynamics of nonlinear oscillators. An algorithm is developed to design a vector field with a stable limit cycle that has a given shape and a given phase sensitivity function. The vector field is approximated by a polynomial whose coefficients are estimated by convex optimization. Linear stability of the limit cycle is ensured by introducing an upper bound on the Floquet exponent. The validity of the proposed method is verified numerically by designing several types of existing and artificial 2D oscillators. As applications, we design a limit-cycle oscillator with an artificial star-shaped periodic orbit and demonstrate its global entrainment to a periodic input. We also design a limit-cycle oscillator with an artificial phase sensitivity function with high-harmonic components, which exhibits multistable entrainment to a periodic high-frequency input.

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CP3

Data Assimilation for Networks of Coupled Oscillators

Many natural phenomena and engineering applications can be described as networks of coupled oscillators, for example, neurons in the brain and the dynamics of the power grid. Here we discuss the adaptation of data assimilation methods (commonly used for weather forecasting) to networks of coupled oscillators. In particular we show that data assimilation can be used to estimate unknown model

parameters in the case where not all oscillators are observed. We also discuss the challenges of data assimilation, and data-based techniques generally, for parameter estimation in networks of coupled oscillators. For instance, convergence to a synchronized state leads to data degeneracy.

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CP3

Binary Synchronization of Randomly Forced Oscillators

Synchronisation of non-locally coupled oscillators has been extensively studied since Kuramoto's model of oscillators was proposed in 1975. This and other traditional models of synchronisation are predicated on deterministic forcing between individuals. Intrinsic randomness of oscillators has been incorporated into the Kuramoto model but this invariably causes a decrease in synchronization. In this talk we will show that, while noise usually creates disorder, systems can reach order through randomness. We propose and analyse a model that reproduces many of the common features of the Kuramoto model around the incoherent state but exhibits binary phase locking instead of full coherence. Using recently developed methods we are able to find exact solutions for the stationary, synchronized state. We also find approximate low dimensional dynamics for this model which qualitatively describes the full system of oscillators.

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CP4

Flow Field Analysis of Nonequilibrium Molecular Reaction Dynamics

I will illustrate the application of flow field analysis to understand the results of classical and semi-classical molecular simulations that are performed under nonequilibrium conditions. In numerous molecular systems that are relevant in technological applications, time-dependent fields, density gradients, and/or thermal gradients push the system toward a nonequilibrium state where equilibrium theories often fail. Accurately determining state transition timescales, i.e., chemical reaction rates, is a critical step for predicting the time evolution of these systems. While there are a number of theoretical methods that can be applied to understand chemical reactions that occur under thermodynamic equilibrium conditions, in nonequilibrium cases there is a void of suitable theoretical approaches. In this talk, I will discuss how Lagrangian flow field analysis can be applied to atomistic trajectories in order to detect the phase space structures governing state transitions in nonequilibrium molecular reactions.

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CP4

Identifiability in Endocrinological Models for Adrenal Support

Adrenal insufficiency is a disorder that occurs when the body struggles to produce enough of certain hormones such as cortisol. Patients with adrenal insufficiency undergo treatment to increase their level of cortisol. However, existing treatment strategies are unable to replicate the physiological profile of cortisol in healthy individuals. Mathematical models of the endocrine (hormone) system aim to use simulations to predict the outcomes of different treatments to reduce the need for clinical trials. We present a simplified model of hydrocortisone delivery via intravenous bolus (IV) and continuous intravenous infusion (CIV). The model is formulated in terms of linear kinetics and considers the dynamics of glucocorticoid-protein binding. We utilise a quasi-steady approximation in the CIV case to rationally reduce the model to assist parameter estimation. For the IV case, we use matched asymptotic expansions to find a slow manifold. A key mathematical challenge when we come to data fitting is accurately inferring the model parameters from data sets that only observe some of the model variables and have limited time resolution. This issue motivates the study of parameter identifiability; can parameters be uniquely estimated from partial, low-resolution, noisy datasets? We hope with this analysis to fit our model parameters to recently published data on 50mg dosing every 6 hours (or a 200mg continuous infusion) using Bayesian inference with the software Stan.

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CP4

Fast-Slow Analysis in Dynamical Systems with Three Time Scales

Dynamical systems describing biological and chemical systems usually prsent large differences in the time scales of their variables. These systems can be studied by classifying their variables as fast or slow and using tools and techniques such as singular perturbation theory, critical manifolds and Fenichel's theory. In this talk, we discuss how, in certain systems, a simple fast-slow analysis is not enough to characterize their dynamical properties. Such is the case of the reduced 3-variable Leo-Rudy model for ventricular cells, for which a standard 1-fast—2-slow analysis fails to properly describe some of its characteristics. Instead, due to the large difference in time scales among the 2 slow variables, those should also be separated, resulting in a 1-fast—1-slow—1-ultraslow decomposition of the variables of the system. We apply the fast-slow techiques to this decomposition, showing how it describes the presence of canards, which gives rise to the creation of Early Afterdepolarizations that may generate cardiac arrhythmia. [Barrio et al. (2022). Bifurcation genesis of early afterdepolarizations in cardiomyocytes: the role of fast-slow decompositions. Preprint, 2022.]

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CP4

Complex Oscillatory Patterns in a Three-Timescale Predator-Prey Model

We consider a two-trophic ecosystem that models the interaction between a specialist predator (one that relies exclusively on a single prey species), a generalist predator (one that takes advantage of alternative food sources in addition to consuming the focal prey species), and their common prey. Assuming that the prey operates on a faster timescale, while the specialist and generalist predators operate on slow and superslow timescales respectively, we portray the model in the framework of singular perturbed system of equations featuring three timescales. Treating the predation efficiency of the generalist predator as the primary varying parameter and the proportion of its diet formed by the prey species under study as the secondary parameter, the system exhibits a host of rich and interesting dynamics, such as relaxation oscillations, mixed-mode oscillations, subcritical elliptic bursting, torus canards, and mixed-type torus canards. Grouping the timescales into two classes and using the timescale separation within the classes, we perform two-timescale analyses to gain insights about the dynamics. Using the geometric properties and singular flows in combination with bifurcation analysis, we classify the oscillatory dynamics and describe the transitions from one type of dynamics to the other.

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CP5

Framework for Global Stability Analysis of Dynamical Systems

In this work we provide an algorithmic interface that finds attractors of dynamical systems, calculates the fractions of their basins of attraction, and continues both the attractors and their basins across a parameter space. This approach is a fundamental improvement of the established linearized bifurcation analysis because it (a) works for any kind of attractors, even chaotic ones, (b) calculates the global (basin) stability of the attractors instead of a linearized, and hence local, stability measure, and (c) is flexible on how to match, or even group, attractors across a parameter range. These features are highly desirable in e.g., systems with coexisting chaotic attractors, or tipping points analysis, as global stability is arguably one of the best indicators of a system approaching tipping, or cases of extreme multistability, such as coupled oscillator networks where aggregating individual attractors is useful. The algorithmic interface improves on existing literature methods and incorporates new approaches, allowing for an accurate yet fast identification and continuation of the actual attractors, not just some descriptive representations of them. We demonstrate the efficacy and superiority of our approach versus other methods on models of climate, power grids, metabolic systems, paradigmatic chaotic models, and more. The interface is available as simple-to-use, well-documented, open-source code as part of the DynamicalSystems.jl software library.

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CP5

Data-Driven Inference of Low Order Representations of Observable Dynamics for An Airfoil Model

We implement an adaptive isostable reduction strategy to obtain a data-driven reduced order model that captures the dynamics of observables in a computational model for fluid flow over an airfoil at moderate Reynolds numbers. The resulting model characterizes the response to both time-varying inflow conditions and Dirichlet boundary conditions on the surface of the airfoil meant to represent suction or blowing through the action of surface jets. The resulting reduced order model behaviors agree well with the dynamics of the full order model simulations in response to both open loop and closed loop inputs. This study provides a proof of concept that reduced order modeling techniques adaptive isostable coordinates can be successfully used in realistic fluid flow models using geometries with practical relevance.

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CP5

Efficient Fixed Point Iterative Schemes and Dynamical Systems

Construction of the efficient fixed point iterative schemes for solving variational inequality problems (VIP) and the development of robust numerical schemes for solving systems of differential equations are active research areas for several years. In this talk, overview of the relationship that exists between dynamical systems and several fixed point iterative schemes will be presented. Furthermore, our recent results on the subgradient-extragradient method with inertial extrapolation terms and self-adaptive step sizes for solving VIP will be discussed. This version is more relaxed with easy to implement conditions on the inertial-factor and relaxation parameter. Examples are provided for implementation and comparison purposes.

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CP5

Matrices, Moments, Quadrature and Dynamical Systems

Krylov subspace spectral (KSS) methods are high-order accurate, explicit time-stepping methods with stability characteristic of implicit methods. This “best-of-both-worlds’ compromise is achieved by computing each coefficient of the solution in some basis using an individualized approximation, based on techniques from “matrices, moments and quadrature’ due to Golub and Meurant for computing bilinear forms involving matrix functions. This talk will present an overview of their derivation and essential properties, and also highlight ongoing projects aimed at enhancing their performance and applicability.

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CP5

Eulerian Approaches for Computing Lagrangian Quantities in Dynamical Systems

We present several recent efficient Eulerian numerical approaches based on the Level Set Method for constructing flow maps in continuous dynamical systems. With the flow map, we can then compute various important Lagrangian-based qualities, such as the finite-time Lyapunov exponent (FTLE), the finite-size Lyapunov exponent (FSLE), and the finite-time escape rate (FTER). The presentation will introduce the fundamental idea of these Eulerian approaches and summarize several recent developments, including flow map construction based on the Eulerian interpolation scheme, using sparse Lagrangian trajectories, and based on velocity measurements with uncertainty.

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CP5

Uncertainty Quantification and Identifiability of ODE-Based Systems

In this talk we provide an overview of the methods that can be used for prediction under uncertainty and parameter calibration of dynamical systems, and of the fundamental challenges that arise in this context. In particular, we raise a warning flag about identifiability of the parameters of ODE-based models; often, it might be hard to infer the correct values of the parameters from data, even for very simple models, making it non-trivial to use these models for meaningful predictions. Most of the points that we touch upon are actually generally valid for inverse problems in general setups, and can be adapted to the case of PDE-based models.

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CP6

Modelling the Estimation of Epidemiologic Dynamics from Cycle Threshold Distributions

The modelling of viral infection has piqued the interest of many researchers, particularly in light of the world’s battle with the COVID-19 pandemic and, more recently, the progressive increase in the global spread of monkeypox disease. This research highlight the population distribution of viral loads observed under random or symptom-based surveillance reverse transcription quantitative polymerase chain reaction (RT-qPCR) tests, which provide semiquantitative results in the form of cycle threshold (Ct) values that change during an epidemic and are an important predictor of pandemic trajectory and dynamics was investigated. The work estimated the epidemic’s trajectory using both statistical modelling (in this case, the branching process and renewal equation) and mathematical modelling (in this case, the exponential model and the SEIR model). The findings presented in this research can help researchers better understand viral disease dynamics.

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CP6

Noise Effects in Epidemic Outbreak Statistics:

Large and Small Fluctuations

Motivated by recent epidemic outbreaks, including those of COVID-19, we solve the canonical problem of calculating the dynamics and likelihood of extensive outbreaks in a population for a large class of stochastic epidemic models, including the susceptible-infected-recovered (SIR) model and its general extensions. In the limit of large populations, we compute the probability distribution for ALL extensive outbreaks including those that entail unusually large or small proportions of a population infected, given both demographic and parameter noise. Our approach reveals that, unlike other well-known examples of large fluctuations occurring in stochastic systems, the statistics of extreme outbreaks emanate from a full continuum of optimal paths satisfying unique boundary conditions. Moreover, we find that both the outbreak variance and the probabilities for extreme outbreaks depend sensitively on the source of noise.

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CP6

The Effects of Public Health Measures on Severe Dengue Cases: An Optimal Control Approach

Caused by four distinct viruses, dengue fever is transmitted through a bite of infected mosquitoes. With more than one-third of the world population at risk of acquiring the disease, We propose a vector-host mathematical model considering multiple virus strains and the mosquito population dynamics. Optimal control theory is used to asses control strategies for disease spreading. A detailed sensitivity analysis (PRCC Method) is conducted in order to identify the key model parameters having more influence on the transmission of the disease. We evaluate the optimal control problem by considering vaccination, non-pharmaceutical preventive measures, and reduction of mosquito population as the available public health control measures. The proposed cost functional includes a weighted sum of several efforts for each specific control measure, including the impact of severe dengue cases. The analysis of control system using Pontryagin‘s Maximum Principle leads to the existence of the optimal control profiles. A comparative study for three different control strategies is conducted with numerical experiments. Our findings ensure that every individual control strategy has its own impact on reducing the cumulative number of dengue infections. The well planed simultaneous use of the available public health interventions measures is highly effective to control the prevalence of severe dengue cases, even when large outbreaks are occurring.

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CP6

HIV Modeling in a Post-COVID World: Developing Mathematical Tools to Confront COVID-19 Related Challenges

Nearly three years since the outbreak of the COVID-19 pandemic, the full extent of its impact is still being understood. Several public health data sources indicate that HIV testing, diagnoses, and prescriptions for prophylaxis and treatment medication dropped in the US in 2020 due to COVID-19 related effects. Understanding the future implications of such disruptions is difficult, as these abrupt changes require us to re-evaluate the many assumptions underlying widely-employed mathematical models used for estimating and projecting incidence and prevalence. This talk will address the development of new mathematical tools to better understand and resolve some of these questions. In particular, we explore two issues: (1) to what extent the drop in new HIV diagnoses in 2020 is due to changes in testing versus changes in incidence; and (2) the effectiveness of expanding the use of self-testing kits to compensate for reduced HIV testing during the pandemic. For the former, we develop and employ a modified back-calculation algorithm. For the latter, we develop a new compartmental model adapted to the difficulties in jurisdictional heterogeneity, data availability, and uncertainty inherent to the problem. Such considerations are important in understanding progress with achieving national HIV prevention goals, and assessing strategies to offset any losses.

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CP7

On the Patterns Produced by Small CPGs

Global and local synchronization patterns in biological processes is key to understanding the dynamics of biological networks. In this talk we present some results we have obtained on global synchronization of small networks of neurons. We are interested in the dynamics of Central Patterns Generators (CPG), small groups of interconnected neurons that produce rhythmic patterns even in the absence of rhythmic input. These groups of neurons control the production of rhythmic patterns like those appearing in the heart beat, chewing, respiration and movement. Here, we explore a Hodgkin-Huxley like model neuron, introduced by Ghigliazza and Holmes, by computing its spike-counting diagrams and the main bifurcations. These techniques give us a ‘roadmap’ for its dynamics. With this we can explore a 6-neuron CPG introduced to model the movement of insects to understand the possible gaits the model can produce. To do so we perform a quasi-Monte-Carlo sweep followed with automatic detection techniques. As a result, we get a complete picture of the patterns and their evolution while changing a parameter. This study reveals the complete dominance of the tripod gait in the region of fast movement regime, like in the real case of insects in Nature. Using continuation techniques we explain the transitions of different gaits in the current CPG. Finally, we explore a family of synthetic CPGs to show that all of them behave similarly.

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CP7

Structural and Dynamical Specializations for High-Frequency Neural Coincidence Detection

A principal cue for sound source location is the difference in arrival times of sounds at an animal's two ears (interaural time difference, ITD). A particularly remarkable example of ITD-selectivity is in the nucleus laminaris (NL) region of the barn owl. Firing rates in these neurons are modulated by the weakly-oscillating, high-frequency inputs that carry ITD information. The functional role of NL neurons in ITD processing is well-known, but the biophysical and dynamical mechanisms that specialize these neurons for high-frequency ITD sensitivity have not been fully described. We use a biophysically-based model to study the effects of soma-axon structure and nonlinear dynamics on ITD processing by NL neurons. First, we show that electrical separation of the soma from the axon region in the neuron enhances high-frequency ITD sensitivity. This soma-axon coupling configuration promotes linear subthreshold dynamics and rapid spike initiation, making the model more responsive to input oscillation amplitude, rather than mean input level. Second, we demonstrate that transforming our model to a phasic firing mode further enhances high-frequency ITD-sensitivity. Similar structural and dynamical mechanisms specialize mammalian auditory brainstem neurons for ITD-sensitivity at lower frequencies, thus our work identifies common principles of ITD-processing across species and for sounds at widely-different frequencies.

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CP7

Regular and Sparse Neuronal Synchronization Are Described by Identical Mean Field Dynamics

Fast neuronal oscillations (¡30 Hz) are very often characterized by a dichotomy between macroscopic and microscopic dynamics. At the macroscopic level oscillations are highly periodic, while individual neurons display very irregular spike discharges at a rate that is low compared to the global oscillation frequency. Theoretical work revealed that this dynamical state robustly emerges in large networks of inhibitory neurons with strong feedback inhibition, and significant levels of noise. This so-called *'sparse synchronization'*, has been traditionally considered to be at odds with the classical theory of collective synchronization of heterogeneous self-sustained oscillators, where synchronized neurons fire regularly. By means of an exact mean field theory for populations of heterogeneous, quadratic integrate-and-fire neurons —that here we extend to include Cauchy noise—, we show that networks of stochastic neurons showing sparse synchronization are governed by exactly the same mean field equations as deterministic networks displaying regular, collective synchronization. Our results reconcile two traditionally confronted views on neuronal synchronization, and upgrade the applicability of exact mean field theories to describe a broad range of biologically realistic neuronal states.

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CP7

A Mathematical Model of Microtubule Assembly and Polarity in Dendrites

The microtubule cytoskeleton is responsible for sustained, long-range intracellular transport of mRNAs and proteins in neurons. However, microtubules must also be dynamic and rearrange their orientation, or polarity, in response to injuries. While mechanisms that control the minus-end out microtubule orientation in Drosophila dendrites have been identified experimentally, it is unknown how these mechanisms maintain both dynamic rearrangement and sustained function. To better understand these mechanisms, we introduce a spatially-explicit mathematical model of dendritic microtubule dynamics using parameters informed by experimental data. We explore several hypotheses of microtubule growth using a stochastic model, and validate such mechanisms with fluorescence experiments. By incorporating biological experiments, our modeling framework can uncover the impact of various mechanisms and parameters on the emergent dynamics and polarity of microtubules in Drosophila dendrites.

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CP7

Alternative Mechanisms for Retaining Phase Cohesion in Coupled Neurons with Synaptic Plasticity

Phase cohesion and synchronization of coupled neurons has been studied extensively in systems with static synaptic coupling strengths. Previous research has focused on computing the critical coupling strength required to retain phase cohesion in a network of inhibitory neurons with static coupling strengths and different natural frequencies. By altering the synaptic coupling strengths to be plastic instead of static, with update rules governed by standard Spike-Timing-Dependent Plasticity (STDP) protocols, the mechanisms for retaining phase cohesion in these spread-

frequency networks notably change. STDP allows for the synaptic coupling strength between neurons to change temporally, strengthening or weakening depending on the time of each neurons respective spikes. We have derived a rigorous upper bound for the critical coupling strength of a network of neurons in this scenario. We tested our results on a small world network of conductance-based neurons with all-to-all plastic synaptic coupling, treating the neurons as oscillators whose dynamics could be analyzed using reduced-order modelling techniques.

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CP8

Bifurcations of Quasiperiodic and Mode-Locked Periodic Orbits

In this talk, I shall deal with the bifurcations of both ergodic and resonant tori in 3D maps. These bifurcations are of four basic types: 1. Two types of doubling: (a) creating two disjoint loops and (b) creating a single closed curve of double the length; 2. creation of a torus in discrete time, which implies the creation of a third frequency; 3. merger and disappearance of a stable and an unstable torus. For resonant tori, the stable fixed points have three eigenvalues: one with eigenvectors in the radial direction, another with eigenvectors tangential to the plane of the loop. Gardini et al. conjectured that the sign of the third eigenvalue determines the type of period doubling: If it is positive we get two disconnected loops and if it is negative we get a length-doubled closed curve lying on the edge of a Mbius strip. We report validation of this conjecture. In explaining the four bifurcations in ergodic tori, we introduce a "second Poincar section" placed in the discrete-time state space, and we observe the nature of the point at which the closed invariant curve intersects this plane. We show that the eigenvalues of this point indicate the type of bifurcation the closed invariant curve will go through. We also demonstrate doubling of a closed invariant curve of infinite length created by a saddle-focus connection.

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CP8

Bifurcation of Attracting Limit Cycles from a Fold-Fold Singularity in Discontinuous Systems with Application to a Glacial Cycles Model

Let f be a discontinuous vector field taking the forms f^+ and f^- on the two sides of the switching threshold L. A fold-fold singularity (or Teixeira singularity,or U-singularity) is such a point x_0 of L where both $f^+(x_0)$ and $f^-(x_0)$ are tangent to L. Under generic conditions, fold-fold singularity persists under perturbations and don't produce any cycles under perturbations. We establish bifurcation of attracting limit cycles from x_0 under an additional (degeneracy) condition that requires $f^+(x_0)$ to be directed opposite to $f^-(x_0)$ (i.e. when fold-fold singularity is simultaneously a switched equilibrium). Related results were obtained earlier in [Cristiano, Pagano, Carvalho, Tonon, J. Differential Equations 268 (2019)]. The focus of our work has been on getting computationally verifiable conditions because the main motivation and application of our results is the Conceptual Model of Glacial Cycles [Walsh, Widiasih, Hahn, McGehee, Nonlinearity 29 (2016)].

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CP8

Bifurcation Structure of Traveling Pulses in Type-I Excitable Media

Excitability is a property of certain nonlinear dynamical systems concerning their response to external perturbations. Excitable systems can be classified into two classes, Type-I and II, with differentiated dynamical properties and obtained through different bifurcations [E. M. Izhikevich, Dynamical Systems in Neuroscience (MIT)Press, Cambridge (MA), (2007)]. Excitable media, locally excitable spatial extended systems, show different regimes in which local perturbations, exceeding a threshold, can propagate across the medium. Many studies consider Type-II excitable media, but much less is known about pulse propagation in the Type-I case. Recently, several vegetation systems compatible with Type-I excitability have shown traveling pulses. We have studied the existence of traveling pulses in a general Type-I excitable 1-dimensional media. We have obtained the stability region and characterized the different bifurcations behind either the destruction or loss of stability of the pulses. In particular, some of the bifurcations delimiting the stability region have been connected, using singular limits, with the two different scenarios that mediated the Type-I local excitability, I.e. homoclinic (saddle-loop) and SNIC (Saddle-Node on the Invariant Circle) bifurcations [P. Moreno, A. Arinyo-i-Prats, D. Ruiz-Reynes, M.A. Matias and D. Gomila, Bifurcation structure of traveling pulses in type-I excitable media, Phys. Rev. E 106, 034206 (2022)].

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CP8

Stability and Bifurcation Analysis of Coherent Structures Arising in Mean-Field Games

Mean Field Games (MFGs) model a continuum of interacting agents, each of whom aims to minimize a cost that depends upon its own state and control effort, as well as the collective state of the population. Mathematically, MFGs are described by a coupled set of forward and backward in-time partial differential equations for state and control distributions, respectively. As the control penalty is varied, the solutions of the closed-loop MFG system can undergo bifurcations, resulting in qualitatively different collective behaviors. We study the stability of coherent states in a non-local model of flocking of intelligent agents with second order dynamics moving in 1D. The bifurcation analysis provides insight into inverse design of collective behavior of large-population multi-agent systems.

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CP8

Exploring Topological Data Analysis for Identifying Phenomenological Stochastic Bifurcations

The state of many engineered and natural systems can transition between several, qualitatively different regimes over time. These transitions (called bifurcations) are important as they can signal harmful transitions in the system's response. In presence of randomness, there is interest in tracking stochastic bifurcations referred to as P-type (Phenomenological) bifurcations. These include transitions from mono-stability to bi-stability, and the emergence of stochastic limit cycles in the probability distributions of the state space. Identifying and analyzing P-type bifurcations is more challenging than their deterministic counterparts. For P-type bifurcations, the prominent practice is to visually inspect the probability density function to judge the type of the bifurcation. This limits the feasibility of this approach to experienced users, and to systems with a small state space (no larger than 2). In contrast, we present an approach based on Topological Data Analysis (TDA) for quantifying P-type bifurcations in stochastic systems. We show examples that demonstrate how measuring the 0- and 1-dimensional sublevel persistence of the probability density function can provide information for inferring P-type bifurcations. We also discuss future work for extending this approach to a wider class of stochastic equations.

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CP8

Using Zigzag Persistence for Bifurcation Detection

Bifurcations in a dynamical system are drastic behavioral changes, thus being able to detect the parameter values for which these bifurcations occur is essential to understanding the system overall. We develop a one-step method to study and detect certain types of bifurcations using zigzag persistent homology. While standard persistent homology has been used in this setting, it usually requires analyzing a collection of persistence diagrams, which in turn drives up the computational cost. Using zigzag persistence, we can capture topological changes in the state space of the dynamical system in only one persistence diagram.

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CP9

Isolating Neighborhood Trajectory Computations in the Non-Autonomous Elliptic Restricted Three-Body Problem

Isolating block and isolating neighborhood methods have previously been implemented to find transit trajectories and orbits around libration points in the autonomous circular restricted three-body problem (CRTBP). These methods have also been used to closely track quasiperiodic orbits and explore chaotic regions around the libration points in the CRTBP. For some applications, the direct computation of these types of trajectories in non-autonomous models more closely approximating real-world ephemerides is beneficial. Here, we apply isolating neighborhood methods to the non-autonomous elliptic restricted three-body problem (ERTBP) and explore the implementation of these models in several different ERTBP models. Specifically, different types of isolating neighborhood boundaries are implemented, and simplified isolating neighborhood boundaries are computed around libration points in the ERTBP. Methods are implemented to verify computationally that these boundaries are isolating neighborhood boundaries, and these boundaries are then used in combination with a bisection method to compute the forward asymptotic trajectories of the isolated invariant set around a libration point. Specific trajectories are then used to track quasiperiodic orbits for some sample basepoints, and results are shown for a range of quasiperiodic orbit types. The quasiperiodic orbits are also characterized across a range of epochs spanning the period of the system.

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CP9

Dynamical Systems Applications to Missions to Detect Life in the Ocean Worlds

Dynamical systems theory has many applications in space mission design using the Three-Body Problem. In this presentation, we discuss some creative orbit designs enabled by leveraging three-body dynamics for missions to the Ocean Worlds of Enceladus and Europa. As two of the most likely places to find life in our Solar System, they are high priority targets for future NASA missions. The Europa Clipper Mission is currently under development at NASA JPL. We use the Circular Restricted Three-Body Problem as our dynamical model. We discuss the various types of orbits useful to these missions. Of special interest are resonant periodic orbits and halo orbits. Resonant periodic orbits are used to design gravity assist tours that can drastically reduce mission fuel costs. Halo orbits allow for special configurations that simplify observation and material collection such as from the volcanic ice jets at Enceladus' South Pole. Quasi-periodic orbits, which exist on invariant tori, add even more possibilities for mission applications. Our newly defined "invariant funnel" concept takes advantage of the dynamics to turn a target into an attractor for orbit insertions and landing. The large entrance of the funnel naturally shrinks down towards the target orbit or landing site without deterministic maneuvers. This greatly simplifies the navigation and reduces the fuel cost. We show an example of a control algorithm applying invariant funnels to reduce total fuel costs.

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CP9

Jupiter-Ganymede and Jupiter-Europa Unstable Resonant Tori In a Restricted 4-Body Model: Analysis and a Search for Transfers

The phenomenon of mean-motion resonance overlapping is crucial for the generation of large-scale chaos and global instability in celestial systems. This instability in turn can be profitably leveraged for the purposes of low-energy space mission trajectory design. Although prior research has studied these phenomena in the context of restricted 3-body models involving a planet, spacecraft, and a single moon, for tours of planets with multiple moons (e.g. Jupiter), a key problem is finding connections between resonances with different moons. This requires a higher dimensional analysis involving unstable tori, as opposed to the unstable periodic orbits found in restricted 3-body problem resonances. This study focuses on characterizing various resonant torus families in a restricted 4-body model including Jupiter, Europa, Ganymede, and the spacecraft. A complicating factor is the presence of secondary resonances, induced by the addition of the second moon to the model, which appear inside the families of unstable resonant tori. We then present results from a search for trajectories between various Jupiter-Ganymede and Jupiter-Europa resonances in a restricted 4 body model.

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CP9

Regularization of the Hill Four-Body Problem with Oblate Bodies

We consider the Hill four-body problem where three massive bodies, all three of oblate shape, form a relative equilibrium triangular configuration, and the fourth body, which is an infinitesimal body orbits in a neighborhood of the smallest of the three massive bodies. We regularize collisions between the infinitesimal body and the smallest massive body, via McGehee coordinate transformation. From the regularization, we find the corresponding energy manifold and illustrate the collision manifold. We further show that the collision manifold undergoes a bifurcation when the oblateness coefficient of the small massive body passes through the zero value. As a motivating example, we consider the dynamics of the moonlet Skamandrios of Jupiter's Trojan asteroid Hektor.

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CP10

Coherence and Incoherence in Real-World Networks

The emergence of order in nature is manifested in different phenomena, and synchronization is one of the best examples. Understanding the role that interactions between entities of a complex system play in synchrony has become a pivotal research question that bridges network science and dynamical systems. Particular attention has been given to the emergence of chimera states, where subsets of synchronized oscillations coexist with others in total asynchrony, as a pure example of the coexistence of order and disorder simultaneously. Based on a symmetry-breaking mechanism, we shed light on the intrinsic structural properties of real-world networks responsible for the emergence of coexisting coherent and incoherent patterns. In particular, we show that such properties are inherited by the ubiquitous strong non-normality that characterizes empirical networks. In this regard, it has been recently discovered that networks from biology (neuronal, metabolic, protein-protein interactions, genetic), sociology (on/offline social networks), ecology (food webs, animal interactions), etc., have matrix-related operators, e.g., adjacency matrix A, which are strongly non-normal $A^T A \neq AA^T$. Here we report that several simultaneously ordered and disordered states, such as amplitude and phase chimeras or oscillons, on the other hand, can spontaneously emerge. Our analytical prediction is validated from simulations from a large dataset of real-world networks.

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CP10

Well Posedness of Non Autonomous Transport Equation on Metric Graphs

Consider a finite network (i.e., of pipelines) where some material is transported along its branches (i.e., pipes). The velocity of the transport depends on a given branch but may also change in time. We would like to know under which condition such a system can be modelled in a way that for any given initial distribution we are able to predict the state of the system in any time. We would also like to obtain stable solutions, that continuously depend on the initial state. In this case we will call our problem well-posed. Such transport problems on networks have already been studied by several authors. The operator theoretical approach by means of abstract Cauchy problems on Banach spaces was initiated by M. Kramar Fijav and E. Sikolya [M. Kramar and E. Sikolya. Spectral properties and asymptotic periodicity of flows in networks. Math. Z., 249(1):139162, 2005]. A first attempt to non-autonomous problems of this kind was performed by F. Bayazit et al. [F. Bayazit, B. Dorn, and M. Kramar Fijav. Asymptotic periodicity of flows in time-depending networks. Netw. Heterog. Media, 8(4):843855, 2013]. We consider transport problems on finite metric graphs with time-dependent velocities along the edges. This is joint work with M. Kramar Fijavz (Ljubljana, Slovenia).

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CP10

Non-Uniform Sampling Methods for Testing Link Prediction Methods on Networks

Link prediction problems are important for helping to recover missing data in networks and have applications in recommendation systems. Most state-of-the-art tests for link prediction methods have only considered uniformly missing data, e.g., removing edges uniformly from the original network. Uniform sampling of random edges is inherently efficient for constructing a representative subgraph. However, uniform sampling might lead to biased outcomes for link prediction because missing data in many real-world scenarios are probably not uniform. For example, there might be missing data centered around specific individuals or communities, so a link prediction scheme developed under uniform sampling may not achieve its optimal performance in another setting. In order to address this shortcoming, we consider a variety of different sampling methods for mimicking real missing data. We apply these sampling methods to over 500 real-world network data sets to generate tests for link prediction algorithms. These networks include social, biological, transportation, information, economic, and technology networks. We show that under different sampling conditions, various link prediction algorithms can yield different levels of accuracy on different types of networks.

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CP10

Bounded-Confidence Models with Adaptive Confidence Bounds

People's opinions change over time as they interact with each other. In particular, individuals are often influenced by others with similar opinions. One can incorporate this phenomenon into models of opinion dynamics by using bounded-confidence models (BCMs), a family of opinion models with continuous-valued opinions. In a BCM, individuals (which are represented by nodes of a network) are influenced only by neighbors whose opinions are within their confidence bound. We introduce two discrete-time BCMs one synchronous (in which all node pairs interact in each time step) and one asynchronous (in which only one pair of nodes interacts in each time step), generalizing the Hegselman–Krause (HK) and Deffuant–Weisbuch (DW) models, respectively with confidence bounds that are heterogeneous and adaptive. We analytically and numerically explore the limiting behaviors of our models, including the confidence-bound dynamics, the formation of clusters of nodes with similar opinions, and the time evolution of the "effective graph,' which is a time-dependent subgraph of the network with edges between nodes that can currently influence each other. We demonstrate that for a wide range of parameters that control the increase and decrease of confidence bounds, our model results in (1) fewer major opinion clusters and (2) more minor opinion clusters in sparser graphs than in the baseline BCMs.

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CP10

Spectral Energy Transfer on Complex Networks and New Perspectives on Synchronization

The Fourier transform and related scale decompositions form the backbone of many types of nonlinear dynamics analysis. But beyond this, they also are the primary lens through which certain physical phenomena are defined and interpreted: in fluid mechanics, a well known example is the turbulent energy cascade, a dynamic consequence of the three-dimensional Navier-Stokes equations in which energy cascades from large injection scales to smaller dissipation scales. Recent developments in graph signal processing, in particular the definition of the graph Fourier transform, allow us to search for similar phenomena in the context of network-based dynamics. To this end, we study a network of coupled nonlinear oscillators and perform spectral filtering and decomposition in a framework akin to the widely utilized large eddy simulation (LES). We show that this framework allows the simple and explicit calculation of scale-space forcings analogous to Leonard, cross, and Reynolds stresses, and observe spectral energy transfer which has dynamic consequences for the systems path to synchronization.

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CP10

Dimension Reduction of Dynamical Systems on Networks Using Various Eigenvectors of Adjacency Matrices

Dimension reduction techniques for dynamical systems on networks are a tool for understanding the original high-dimensional dynamics. One strategy of dimension reduction is to derive a low-dimensional dynamical system whose behavior approximates the observables of the original dynamical system that are weighted linear combinations of the state variables at the different nodes. Recently proposed such methods employ the leading eigenvector of the adjacency matrix of the network, or its approximation using the individual nodes' degrees, as the mixture weights to obtain such observables. However, the original theory does not formally require that the eigenvector employed be the leading one. Here we theoretically and numerically examine performances of this type of one-dimensional reductions of dynamical systems on networks when we use non-leading eigenvectors of the adjacency matrix as the mixture weights. Our theory predicts that non-leading eigenvectors can be more efficient than the leading eigenvector and also provides us with a method for selecting the eigenvector minimizing the error. We verify that the optimal non-leading eigenvector outperforms the leading eigenvector by running numerical simulations for some dynamical systems and networks. We also show that, despite our theory, it is practically better to use the leading eigenvector as the mixture weights to avoid misplacing the bifurcation point too distantly and in the presence of dynamical noise.

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CP11

Quasi-Ergodicity of Transient Patterns in Stochastic Reaction-Diffusion Equations

We study transient patterns appearing in a class of SPDE using the framework of quasi-stationary and quasi-ergodic measures. In particular, we prove the existence and uniqueness of quasi-stationary and quasi-ergodic measures for a class of reaction-diffusion systems perturbed by additive cylindrical noise. We additionally prove a quasi-ergodic theorem, and under certain conditions, demonstrate that the rate of convergence to a quasi-ergodic average is exponential in time. These results allow us to qualitatively characterize the behaviour of these systems in neighbourhoods of an invariant manifold of the corresponding deterministic systems at some large time t¿0, conditioned on remaining in the neighbourhood at time t. The approach we take here is based on spectral gap conditions, and is not restricted to the small noise regime. Additionally, we discuss how the approach taken here opens up the possibility of characterizing metastability in SPDE using a simple variational approach.

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CP11

Vectorial Reconstruction of Electromagnetic Wave Fields from Time Series Data in the Presence of a Stochastic Current Density

We consider the problem of reconstructing vectorial electromagnetic waves (i.e., solutions of the vector Maxwell equations) from sensor time series data in the presence of a noisy current density, which is represented by a cylindrical Wiener process. The noise variance increases with time in the resulting infinite dimensional, nonequilibrium system. In such cases, longer observation times do not provide better reconstructions of the dynamics. Rigorous closed-form expressions are derived for the variance of the reconstruction error in useful special cases. Because the reconstruction error decreases as a function of time in the absence of noise and increases in the presence of noise, in general there is an optimal observation time that minimizes the reconstruction error. We demonstrate an iterative algorithm to solve for the amplitudes of different frequency waves of the electric field using the optimal observation time. These results extend our work on sensor reconstruction of wave dynamics [Bryce M. Barclay, Eric J. Kostelich, and Alex Mahalov. Sensor placement sensitivity and robust reconstruction of wave dynamics from multiple sensors. SIAM Journal on Applied Dynamical Systems, accepted 2022].

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CP11

Generative Model Assisted Sampling of Multiscale Stochastic Dynamical Systems

Sampling the phase space of molecular systems – and, more generally, of complex dynamical systems effectively modeled by stochastic differential equations – is a crucial modeling step in many fields from protein folding to materials discovery. These problems are often multiscale in nature: they can be described in terms of low-dimensional effective free energy surfaces parametrized by a small number of "slow" reaction coordinates; the remaining "fast" degrees of freedom populate an equilibrium measure on the reaction coordinate values. Over the years, enhanced sampling techniques coupled with molecular simulation have been developed. An intriguing analogy arises with the field of Machine Learning (ML), where generative models such as Generative Adversarial Networks (GANs) and Score-Based Diffusion Models can produce high dimensional samples from low dimensional probability distributions. This sample generation returns plausible high dimensional space realizations of a model state, from information about its low-dimensional representation. We present an approach that couples physics-based simulations and biasing methods for sampling conditional distributions with ML-based conditional generative models for the same task. The "coarse descriptors" on which we condition the fine scale realizations can either be known a priori, or learned through nonlinear dimensionality reduction.

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CP11

Improving Accuracy of Stochastic Collocation in ODE/PDE Systems via Data-Driven Factorization of the Model Dynamics

Stochastic collocation (SC) is a popular uncertainty quantification (UQ) framework for constructing surrogate models of expensive computational models; it is easy to implement in an online and nonintrusive fashion. It approximates quantities of interest (QoI) by interpolation using a few exact simulations corresponding to collocation points of uncertain model parameters/stochastic dimensions. However, the accuracy of this approach decreases rapidly as the nonlinearity of the parameter-to-QoI map increases. For systems modeled by differential equations, we propose to approximate the dynamics (instead of the QoI) within the SC framework, for the purpose of efficiently propagating model parameter uncertainty (forward UQ). Since the functional dependence of the dynamics on the model parameters is usually less complex than that of the QoI, we expect to obtain more accurate surrogates for the UQ task. We use a data-driven factorization of the dynamics, separating the state from the model parameters, and apply the SC to the learned dynamics. We demonstrate that this approach leads to smaller errors than direct SC for various ODE/PDE based dynamical systems with minimal intrusion to the application code. In particular, we apply our method to approximate trajectories from chaotic Lorenz ODE and solid mechanics PDE simulations; in both cases the prediction accuracy improves by several orders of magnitudes. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

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CP11

A Nonlinear Stochastic Heat Equation with Variable Thermal Conductivity and Multiplicative Noise

We consider a stochastic heat equation with variable thermal conductivity, on infinite domain, with both deterministic and stochastic source and with stochastic initial data. The stochastic source is given in the form of multiplicative generalized stochastic process. We use regularized derivatives and the theory of generalized uniformly continuous semigroups of operators in solving procedure. We prove that a unique solution exists in a certain space of generalized stochastic processes. We justify our procedure by proving that, under certain conditions, the operators of non-regularized and the corresponding regularized problems are associated.

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CP11

Stochastic Stabilization and Disturbance Observer Based Disipativity for Interval Type -2 Fuzzy Stochastic Systems with Multiple Disturbances and Uncertainities

Anti disturbance control design problem is proposed for a class of interval type-2 fuzzy stochastic systems subject to uncertainity and multiple disturbances. A fuzzy exogenous system takes into account a new fuzzy disturbance observer in order to precisely evoke the properties of interval type 2 fuzzy stochastic models with multiple disturbances. The fuzzy feedback controller scheme is constructed with asynchronous premise variables which does not share the membership functions with the membership functions of the plant. In order to ensure the stochastic stability of the closed loop fuzzy system, a new sufficient condition is constructed using the method of linear matrix inequalities by integrating the *Itô* operator and choosing the appropriate Lyapunouv-Krasovskii functional candidate with $(\mathcal{Q}, \mathcal{S}, \mathcal{R}) - \epsilon$ dissipativity performance index. Finally, the provided theory is then demonstrated for the Mass Spring Dashpot system and also the effectiveness is supported with the comparitive study between T-S fuzzy and type-2 fuzzy for the same model.

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CP12

Four Dimensional Variational Data Assimilatoin

Using Koopman Operators

In this work we present the use of Koopman eigenfunctions in four-dimensional data assimilation (4D-Var) to simplify the required optimization and avoid the need for adjoint models. Data assimilation are methods that combine information from a model and observations to produce a accurate forecast or prediction of the phenomena of interest. One of the most effective data assimilation methods is the 4D-Var, which uses information available within a time window to calibrate the model inputs (initial conditions, parameters, etc.) in order to improve the forecast of the model. In essence the 4D-Var is an optimization problem that uses a penalizing or cost functional which measures the difference between the model prediction and available observations. The necessary model derivative needed for the optimization is computed through the adjoint model. In this talk we use the Koopman eigenfunctions to approximate the derivative of the model, and reduce the space within which the optimization is performed. We present results with a 2-dimensional shallow water model, where we compare our Koopman eigenfunction approach with the more traditional approach using the adjoint model. The results show that the Koopman eigenfunctions provide a reasonable result in the 4D-Var optimization, and hence is comparable to the use of the adjoint model.

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CP12

Koopman-Based Modeling and Control of Nonlinear Soft Robots

Compared to traditional, rigid robots, soft robots offer inherent compliance that gives these robots the ability to work safely in close proximity with humans. However, the flexibility of soft robots induces highly nonlinear dynamical behavior which makes them very difficult to model and control. Considering also the infinite number degrees-of-freedom present in such systems, obtaining mathematical models grounded on first-principles and knowledge of material properties is very difficult and generally enables their operating only in linear regime (low deflection and low velocity). To address the above listed issues, a data-driven learning approach based on the Koopman operator framework is used to identify the model of pneumatically driven soft arm. The arm is equipped with a motion capture system to measure its position in workspace. An Extended Dynamic Mode Decomposition (EDMD) with time delay observables is applied to obtain a finite dimensional approximation of control Koopman operator. Such approach results in a globally linear model of the nonlinear soft robot dynamics using only a couple of minutes of training data generated by random step inputs. Based on the obtained linear model, a simple linear state feedback controller is developed and precise, fast, high-deflection displacements to arbitrary reference positions commanded in real-time are achieved.

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CP12

Physics-Informed Koopman Network

Koopman operator theory is receiving increased attention due to their promise to linearize the nonlinear dynamics. Neural networks that were developed to represent Koopman operators are of great success thanks to their capability of approximating arbitrarily complex functions. However, despite their great potential, they typically require large training data-sets either from measurements of a real system or high-fidelity simulations. In this work, we propose a novel architecture inspired by the physics-informed neural network, which leverages automatic differentiation to impose the underlying physical laws via soft penalty constraints during model training. We demonstrate that it not only reduces the need of large training data-sets, but also maintains high effectiveness in approximating Koopman eigenfunctions.

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CP12

Koopman Analysis of Quantum Systems

Koopman operator theory has been successfully applied to problems from various research areas such as fluid dynamics, molecular dynamics, climate science, engineering, and biology. Most applications of Koopman theory have been concerned with classical dynamical systems driven by ordinary or stochastic differential equations. In this presentation, we will first compare the ground-state transformation and Nelson's stochastic mechanics, thereby demonstrating that data-driven methods developed for the approximation of the Koopman operator can be used to analyze quantum physics problems. Moreover, we exploit the relationship between Schrdinger operators and stochastic control problems to show that modern Koopman-based methods for bilinear stochastic control can be used to solve the stationary or imaginary-time Schrdinger equation. Our findings open up a new avenue towards solving Schrdinger's equation using recently developed tools from data science.

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CP12

Dynamics of Nonnegative Matrices in Max Algebra

In this talk, we aim to understand the dynamics of matrix products in max algebra. A consequence of Perron-Fröbenius Theorem on periodic points of a non-negative matrix is generalized to a max algebra setting. It is a joint work with my co-authors Sachindranath Jayaraman and Shrihari Sridharan.

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CP12

Control of Koopman Bilinearized Nonlinear Systems

Koopman operators, since introduced by Bernard Koopman in 1931, have been recognized as a powerful tool for analyzing spectral properties of ergodic dynamical systems. The purpose of this work is to expand the scope of Koopman operator theory to accommodate control-theoretic analysis and tasks. In particular, we introduce Koopman bilinearization for nonlinear control-affine systems. Our development is based on revealing the partial differential equation (PDE) system, governing the dynamics of the Koopman operator associated with a nonlinear control-affine system, as a bilinear system defined on an infinite-dimensional Lie group. Moreover, by integrating techniques from infinite-dimensional differential geometry into geometric control theory, the proposed Koopman bilinearization framework offers a two-fold benefit to control systems analysis: (i) characterization of controllability for control-affine systems in terms of de Rham differential operators, and (ii) extension of the Lie algebra rank condition (LARC) to infinite-dimensional bilinear systems. Our approach fully utilizes the intrinsic algebraic and geometric properties of Koopman operators without requiring measure-preserving and ergodicity assumptions on the system dynamics, which is a manifestation of the distinctive feature of this work.

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CP13

A Nonlinear Delay Model for Explaining Metabolic Oscillations in Yeast Cells

We introduce time-delay models using both constant and state-dependent delays to explain metabolic oscillations in yeast cells. With minimal resources available in the cell, it needs to prioritize the production of proteins that are most important. As a result, oscillations occur in the protein production. We start with a one-protein model with a constraint equation governing the total resource available to the cell. Numerous input parameters make it challenging to search for parameter combinations that yield an oscillatory response. We numerically explore the basins of attraction and study the stability of the linearized equations using the spectral element approach—a semi-analytical tool for studying the stability of Delay Differential Equations (DDE). Our results show that using this model, certain combinations of total resource available to the cell and the time delay lead to limit cycles whereby the equilibrium solution loses stability via Hopf bifurcation. We then extend our model to include three coupled proteins to further explore the ability of our model to explain metabolic oscillations.

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CP13

Defcats: Delay Embedded Forecasting of Chaotic Time Series

Forecasting the future evolution of chaotic data-based systems is a crucial but challenging practical problem. Existing solutions, such as Recurrent Neural Networks (RNNs) or Reservoir Computing (RC), are effective in forecasting time series but require several parameters and hyperparameters. This work discusses a time delay-embedded, parameter-free machine learning approach to chaotic time series forecasting which leverages Extra-Trees Regressors (ETRs). The benefits of ETR-based regression are resilience to correlation in features and the ability to measure feature importance. Our proposed algorithm trains an ETR on delay-embedded time series data and leverages feature importances to select those time delays which provide predictive power. By training an additional ETR on the reduced features, we may perform forecasting by recursively predicting with and appending to the time-delayed features. We provide a basis for tuning the delay embedding using average mutual information while demonstrating the efficacy of our proposed algorithm using toy models, such as the Lorenz system and the logistic map, and challenging problems, such as the spatiotemporal Kuramoto-Sivashinsky system and real-world Southern Oscillation Index. Our proposed algorithm shows excellent performance compared to existing methods, eliminating the need to search a high-dimensional parameter space.

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CP13

Exploring Mechanisms of Chaos in Delayed Oscillator Systems with Cubic Nonlinearity

Chaotic behavior has previously been shown to occur within oscillating systems governed by first-order delay differential equations, such as the Ucar system $\dot{x}(t) = \delta x(t-\tau) - \epsilon[x(t-\tau)]^3$ where parameters δ and ϵ are taken to be positive. Considering the same equation with negative values for δ and ϵ, we observe that the stability profile of the equilibrium solutions changes, and thus the Hopf bifurcation creating a stable limit cycle occurs at a different equilibrium point. However, by adjusting the delay parameter τ, we find that chaos also occurs within this variant of the system. In this talk, we will compare the chaotic behaviors of this equation within the two parameter regimes. By also considering variations of the equation with delay/non-delay combinations of the cubic nonlinearity $(x(t)[x(t-\tau)]^2$, $[x(t)]^2 x(t-\tau)$, and $[x(t)]^3)$, we will discuss how the nature of the three equilibrium solutions might influence the presence of chaos.

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CP13

Self-Induced Synchronization by Time Delay

This workdeals with periodic behavior of differential equations with time delay. Starting from a smooth vector field f in $\mathbb{R}^n$ admitting a stable periodic orbit Γ, we look at the trajectories of the perturbed delay equation $\dot{x} = f(x) + \eta g[x, x(t-\tau)]$ where the parameter η is small and the delay τ is large so that $\eta\tau$ be bounded but not small. We prove that asymptotically, the trajectories starting in a neighborhood of Γ of size independent on η and τ (in the space of continuous functions over $[-\tau, 0]$), all converge to a periodic orbit, and that all those periodic orbits exist in finite number. We give a formulafor the frequencies of these periodic orbits, valid at first order in η.Hence trajectories present a form of asymptotic synchronization induced by the time delay, although there is no network structure in this setting. Our approach uses in a large part classical nonlinear dynamical systems methods valid for ODEs. It is based on persistence results for semi-flows on Banach spaces due to P. Bates, K. Lu and C. Zeng, and on a construction of an invariant, globally attracting manifold for the semi-flow of our equation (similar constructions have been done in the past in more general settings notably byX.-Y Chen, J. K. Hale, and B. Tan). This work somehow completes already known results on reappearance of periodic orbits in time-delay equations due to S. Yanchuk andP. Perlikowski.

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CP13

Delay Induced Swarm Pattern Bifurcations in Mixed Reality Experiments

Natural swarms exhibit patterns in a variety of forms and have inspired researchers to understand how simple organisms produce complex, emergent patterns occurring when individual organisms follow simple dynamics and local communication rules. Our work provides a model for swarming behavior of coupled mobile agents with communication-time delay which exhibits multiple dynamic patterns in space, which depend on interaction strength and communication delay. A mean field model is used, based on statistical mechanics principles and applies to large numbers of networked agents. A thorough bifurcation analysis has been carried out to predict parameter regions where various patterns occur. We extend this work to robotics applications in a mixed-reality framework in which real and simulated robots communicate in real time creating the self-organized states predicted by the theory.The mixed-reality framework allows for systematic and incremental introduction of real-world complexity by coupling a few real robots and a large number of virtual robots.

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CP14

Self-Segregation in Heterogeneous Metapopulation Landscapes

Complex interactions are at the root of the population dynamics of many natural systems, particularly for being responsible for the allocation of species and individuals across apposite niches of the ecological landscapes. On the other side, the randomness that unavoidably characterises complex systems has increasingly challenged the niche paradigm providing alternative neutral theoretical models. We introduce a network-inspired metapopulation individual-based model where the density of individuals in the hosting patches drives the individuals spatial assembling while still constrained by nodes saturation. We prove that the coreperiphery structure of the networked landscape triggers the spontaneous emergence of vacant habitat patches, which segregate the population in multistable patterns of isolated communities separated by empty patches. Furthermore, a quantisation effect in the number of vacant patches is observed as the total system mass varies continuously, emphasising thus a striking feature of the robustness of population stationary distributions. Notably, our model reproduces the patch vacancy found in the fragmented habitat of the Glanville fritillary butterfly, an endemic species of the land islands. We argue that such spontaneous breaking of the natural habitat supports the concept of the highly contentious (Grinnellian) niche vacancy and also suggests a new mechanism for the endogeneous habitat fragmentation and consequently the peripatric speciation.

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CP14

Dynamical Models for the Cross-Talk with the Extracellular Matrix and Metabolic Pathways

The nutrient availability, growth factor signaling, extracellular matrix composition and architecture heavily affects the metabolic state of the cells. The maintenance of the ECM architecture strictly relies on the availability and production of several metabolites, like the UDP-N-acetylglucosamine, that is essential for the synthesis of hyaluronic acid and directly involved in the glycosylation of proteins. Thus, this pathway plays a pivotal role in metabolism, health, and aging. Chemical reaction network models are a powerful tool for investigating the behavior of complex chemical systems, such as the biochemical pathway involved in the regulation of gene expression, protein regulation, and metabolism. In the current presentation, we are introducing dynamical models for the study of the regulation of the metabolism depending on the mechanical and composition properties of the ECM. To pursue these results, we are encoding the network dynamics using PySB, a Python-based framework for building mathematical rule-based models of biochemical systems. More in detail, each pathway can be encoded as a separate Python program and consequently calibrated. This approach will drive the validation of different hypotheses, such as the independent functioning of the metabolic and signaling pathway.

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CP14

Reaction-Diffusion Modeling of E. Coli Colony Growth Based on Nutrient Distribution and Agar Dehydration

The bacterial colony is a powerful experimental platform for broad biological research, and reaction-diffusion models are widely used to study the mechanisms of its formation process. However, there are still crucial factors that will drastically affect the colony growth, but current models fail to consider, such as the non-homogeneously distributed nutrient within the colony and the substantially decreasing expansion rate caused by agar dehydration. In our study, we propose two plausible reaction-diffusion models based on the above two factors and validate them against experimental data. Both models provide a plausible description of the non-homogeneously distributed nutrient within the colony and outperform the classical Fisher-Kolmogorov equation on experimental data fitting. Moreover, by accounting for agar dehydration, the second model (the MVN model) captures how a colony's expansion slows down the change of a colony's height profile over time. Furthermore, we demonstrate the existence of a traveling wave solution for the first model (the VN model).

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CP14

Tractable Signatures of Evolutionary Selection Methods

Modeling population-level evolutionary dynamics is one of the oldest, and most enduring forms of mathematical biology. Key to many of these models is the notion of different strains having different 'fitnesses,' which represents their net competitive advantages in the environment. For example, in lymph nodes, we know that B cells have a competitive advantage when they can successfully neutralize pathogens. However, reducing this advantage to a singular 1D fitness is misleading, since there may be multiple mechanisms that lead to this advantage. Three simple, potential selection methods include encouraging the reproduction of high affinity cells ('birth selection'), encouraging cell death in low affinity cells ('death selection'), and adjusting the mutation rate based on cell affinity ('mutational selection'). Moreover, multiple methods can be active at the same time, and while all three forms of selection would lead to a net increase in affinity, different selection methods lead to distinct statistical outcomes. We discuss ramifications of different evolutionary models, and encourage thinking about evolutionary fitness as more than a singular number.

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CP14

Minimal Reaction Schemes Exhibiting Turing Instabilities

Turing instabilities in spatially continuous media are often studied through illustrative systems of differential equations for two (or more) scalar variables corresponding to the concentrations of interacting chemical species, for example the Schnakenberg or Brusselator models. These models contain polynomial nonlinear terms of cubic order which imply, at the level of individual chemical reactions, three molecules interacting simultaneously. Such trimolecular reactions are however, improbable and therefore unphysical. Further, their high order can complicate spatial simulations of reaction-diffusion systems. Arguments that cubic terms might arise due to the formation of intermediate complexes serve only to increase the conceptual complexity of the underlying processes. By focussing on simple PDE models of two-species systems under the assumptions of mass-action kinetics and large particle numbers, we show that trimolecular reactions are in fact not necessary for a Turing instability to occur. Restricting to only elementary reaction types, and by recasting the local linear stability and spatial instability conditions into requirements on reaction stoichiometries, we are able to establish necessary conditions for Turing instability. In turn, this allows us to deduce necessary reactions with particular reactant combinations and net stoichiometric effects that must be present. In conclusion we are able to present a classification of 'minimal' Turing-unstable reaction schemes.

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CP15

Phase-Amplitude Coordinate Based Neural Networks for Inferring Oscillatory Dynamics

Phase-amplitude coordinates can be utilized as an efficient model reduction framework to represent oscillatory dynamics of a periodic non-linear system in a low-order basis and allow to investigate the model dynamics beyond the limit cycle. If the model equations are known, it is relatively straightforward to construct a phase-amplitude reduced model up to arbitrary order of accuracy. In this work, it is assumed that only observable temporal data is available and hence, we propose to use feed-forward neural networks to infer coefficients for the phase-amplitude coordinate based reduced model to efficiently emulate the full order dynamics. By framing the set of phase and isostable equations in such a way that the unknown coefficients correspond to the weights of the neural network, one can train the neural network using the observable data to learn the coefficients and ultimately identify a reduced order model representation valid to desired order of accuracy. Finally, for validation purposes, the proposed strategy is illustrated through different models and utilized in conjunction with adaptive phase reduction while considering the dynamics of a synaptically coupled neuronal population.

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CP15

Oscillatory Translational Instability of Localized Spot Patterns in the Schnakenberg Reaction-Diffusion System in Defected 3D Domains

For a two-component reaction-diffusion system in a bounded $3D$ domain, we investigate oscillatory instabilities of N-spot equilibrium. An N-spot equilibrium consists of localized spots in which the activator concentration is exponentially small everywhere except localized regions. We find that stability of these solutions is governed by a $3N \times 3N$ nonlinear matrix eigenvalue problem. Entries of the $3N \times 3N$ matrix involves terms calculated from certain Greens function that contains information about the domains geometry. In the nonlinear matrix eigenvalue system, the most unstable eigenvalue decides the oscillation frequency at onset while the corresponding eigenvector determines the mode of spot oscillations. We further demonstrate the impact of various types of localized domain defects on this instability. Perturbation techniques is employed to compute Greens function of near-spherical and near-cubic domains to gain analytic insight into how domain geometry select the dominant mode of oscillation. We show full solutions of the $3D$ Schnakenberg PDE to confirm our asymptotic results.

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CP15

Inferring Oscillator's Phase and Amplitude Response from a Scalar Signal Exploiting Test Stimulation

The phase sensitivity curve or phase response curve (PRC) quantifies the oscillator's reaction to stimulation at a specific phase and is a primary characteristic of a self-sustained oscillatory unit. Similar, though much less studied characteristic, is the amplitude response that can be defined either using an *ad hoc* approach to amplitude estimation or via the isostable variables. Here, we discuss the problem of the phase and amplitude response inference from observations using test stimulation. Although PRC determination for noise-free neuronal-like oscillators perturbed by narrow pulses is a well-known task, the general case remains a challenging problem. Even more challenging is the inference of the amplitude response. This characteristic is crucial, e.g., for controlling the amplitude of the collective mode in a network of interacting units – a task relevant to neuroscience. Our main result is a novel technique based on the direct reconstruction of the Winfree equation and the analogous first-order equation for isostable

dynamics. The technique works for signals with or without well-pronounced marker events and pulses of arbitrary shape; in particular, we consider charge-balanced pulses typical in neuroscience applications. Moreover, this technique is superior for noisy and high-dimensional systems. Additionally, we describe an error measure that can be computed solely from data and complements any inference technique.

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CP15

Optimal Phase-Selective Entrainment of Heterogeneous Oscillator Ensembles

The ability to organize and finely manipulate spatiotemporal structures in networks of oscillators is a fundamental but challenging task in diverse fields from chronobiology and power systems to social networks. In this work, we consider commonly used phase models and present a unified framework for designing optimal entrainment signals that create stable phase patterns in an ensemble of heterogeneous oscillators. We explicitly take into account heterogeneity in both oscillation frequency and the type of oscillators characterized by different Phase Response Curves. The central idea is to leverage the Fourier series representation of periodic functions to decode a phase-selective entrainment task into a quadratic program. We demonstrate our approach by entraining heterogeneous oscillator ensembles into distinct spatiotemporal structures. Also, we show how the generalizability gained from our formulation enables us to meet a wide range of design objectives and constraints, such as minimum-power, fast entrainment, and charge-balanced controls.

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CP15

A Common Pathway to Cancer: Oncogenic Mutations Abolish P53 Oscillations

The tumor suppressor p53 oscillates in response to DNA double-strand breaks, a behavior that has been suggested to be essential to its anti-cancer function. Nearly all human cancers have genetic alterations in the p53 pathway; a number of these alterations have been shown to be oncogenic by experiment. These alterations include somatic mutations and copy number variations as well as germline polymorphisms. Intriguingly, they exhibit a mixed pattern of interactions in tumors, such as co-occurrence, mutual exclusivity, and paradoxically, mutual antagonism. Using a differential equation model of p53-Mdm2 dynamics, I employ Hopf bifurcation analysis to show that these alterations have a common mode of action, to abolish the oscillatory competence of p53, thereby impairing its tumor suppressive function. In this analysis, diverse genetic alterations, widely associated with human cancers clinically, have a unified mechanistic explanation of their role in oncogenesis. In this talk, I will also discuss the role of physiological oscillations in health and disease broadly.

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CP16

Geometric and Topological Effects on Swarming Dynamics

Swarming patterns that emerge from the interaction of many mobile agents are a subject of great interest in fields ranging from biology to physics and robotics. In many application areas, agents are effectively constrained by such factors as communication network topology and surface geometry, both of which can significantly affect collective-motion patterns and their stability. In this talk we propose a general model for networks of self-propelled swarms moving on surfaces using Lagrangian mechanics. We find that the combination of self-propulsion, friction, network-mediated interactions, and surface curvature produce general milling patterns where each agent in a swarm oscillates on a limit cycle, with different agents splayed along parametrically-related cycles such that a swarms center of mass remains stationary. Using bifurcation and mean-field techniques, we show how these milling patterns lose stability in characteristic ways, either by the "shedding" of weakly connected agents or the formation of unstable spatio-temporal oscillations.

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CP16

The Chaotic Milling Behaviors of Interacting Swarms After Collision

We consider the problem of characterizing the dynamics of interacting swarms after they collide and form a stationary center of mass. Modeling efforts have shown that the collision of near-head-on interacting swarms can produce a variety of post-collision dynamics including coherent milling, coherent flocking, and scattering behaviors. For instance, analysis of the transient dynamics of two colliding swarms has revealed the existence of a critical transition whereby the collision results in a combined milling state about a stationary center of mass. In this work, we show that the collision dynamics of two swarms that form a million state transitions from periodic to chaotic motion as a function of repulsive force strength and its length scale. In particular, using dynamical systems methods we show the onset of deterministic chaos as a function of repulsion strength, the effective modal dimension chaos lives in, and quantify how each swarm is embedded in the other when both swarms combine to form a mill after the collision.

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CP16

Modeling and Steering Multi-Dimensional Opinion Networks with Aggregated Measurements

Opinions of individuals in a population evolve with time and understanding their dynamic behavior can help address challenges pertaining to detecting and mitigating an adversarial input (e.g., dis/misinformation), influencing the opinions of a large population. However, modeling the opinions of a group of individuals over time is a challenging problem. Fundamental challenges are due to the severely sparse, aggregated, and irregular nature of the (anonymous) opinion feedback (data) from individuals in the population (e.g., via surveys) and their inherent nonlinear dynamics (e.g., topic dependencies) driven by complex social interactions. Furthermore, the application of customized intervention (control) to everyone in the population may not always be a feasible option. On the contrary, information dissemination at scale (i.e., using one or a few control signals (e.g., social media posts) might be the only possible intervention strategy in many practical situations. In this work, we view some of the commonly used opinion dynamic models from an ensemble systems perspective and develop data-integrated learning strategies for modeling, reconstructing, and controlling an opinion ensemble using sparse and incomplete feedback data. We demonstrate the feasibility of the proposed approach using numerical simulations and identify the challenges associated with conducting real-world experiments for understanding the effect of false information on the evolution of opinions in a population.

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CP16

Solvable Model of Non-Identical Swarmalators

We study a model of nonidentical swarmalators, generalizations of phase oscillators that both sync in time and swarm in space. The model produces four collective states: asynchrony, sync clusters, vortexlike phase waves, and a mixed state. These states occur in many real-world swarmalator systems such as biological microswimmers, chemical nanomotors, and groups of drones. We provide the first analytic description of these states and conditions for their existence. We show how this approach may be used in studies of active matter and related disciplines.

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CP16

Complex Network Measures Indicate Optimal Targets for Deep Brain Stimulation and Identify Communities of Collective Brain Dynamics

In this study, we build a large-scale computational model for movement disorders that consists of the basal ganglia area, striatum, thalamus, and motor cortex, using connectivity from multimodal medical imaging data. Exploiting the structural properties of the network, we identify nodes of strong influence, which are potential targets for Deep Brain Stimulation (DBS). Simulating the volume of the tissue activated, we confirm that the proposed targets are reported as optimal targets (sweet spots) to be beneficial for improving motor symptoms. Furthermore, based on a modularity algorithm, network communities are detected. It allows us to localize the neural activity directly from the underlying structural topology and highlight the relation between structural and functional connectivity in disorders such as Parkinson's disease. Finally, the application of topological data analysis (TDA) to explain the dynamical organization of the network during healthy and Parkinsonian states will be discussed.

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CP17

Nonlinear Dynamics in Vibrational Energy Harvesting Devices

Microscopic Energy Harvesting Devices are designed to convert mechanical energy from ambient vibrations into electrical energy, which is then used to power small electronic devices, for example wireless sensor nodes. In many natural environments, the frequency content and amplitudes of the ambient vibration will either change over time or will be difficult to characterize beforehand. Nonlinear vibrational energy harvesting devices promise a high efficiency over a broad range of non-stationary external vibration. However, the nonlinearity also gives rise to complex dynamical features which makes the resulting device difficult to understand and control. For example a number of different energy branches might co-exist, with the most efficient one being "hidden', i.e. not accessible by simple frequency sweeps. Typically branches appear as fixed-points in a suitable Poincare map of the external drive and their stability and existence is governed by bifurcations in the drive parameters. In this presentation we show how the use of methods from nonlinear dynamics allows us to discover, characterize and access previously hidden high-energy branches. In particular the use of suitable force-displacement diagrams lets us visualize the transacted energy per cycle for a given energy branch both theoretically and experimentally. This allows us to exploit non-linear dynamics to design highly efficient nonlinear energy harvesting devices.

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CP17

The Spatiotemporal Chaos of Coupled Maps: Insights from the Covariant Lyapunov Vectors

Many open questions remain regarding the spatiotemporal chaos of large systems driven far-from-equilibrium. The high dimension of many systems makes a fundamental computational study prohibitive if it is desired to explore systems with many degrees of freedom, to quantify variations over a range of parameters, and to compute important theoretical quantities which are often a large calculation on their own. This is particularly relevant for fluid systems such as shear flows and thermal convection which remain the focus of intense experimental investigation. However, coupled map lattices (CMLs) provide an accessible route to explore high dimensional dynamics where fundamental questions can be addressed. The physical ingredients of the CMLs can be tailored to contain essential forms of nonlinearity and specific types of spatial couplings. We use CMLs to investigate high-dimensional chaos to build insights into the roles of convective and diffusive couplings. We use the covariant Lyapunov vectors (CLVs) to quantify the tangent space dynamics and to compute the dimension, the degree of hyperbolicity, and the possible decomposition of the dynamics into physical and transient modes. We explore how the couplings affect the CLVs and the chaotic dynamics in physical space. Supported by NSF CMMI-2138055.

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CP17

Analyzing Mixing and Chaos on Continua with Symbolic Dynamics

One of the key challenges in applied mixing problems is identifying when the presence of certain qualitative dynamical features in a system, like chaos, imply that mixing and/or chaotic behavior occur everywhere in the region under consideration. One of the simplest mechanisms for analyzing such qualitative dynamical features is through conjugacy to symbolic dynamical models; however, the traditional formulation of those symbolic systems presents fundamental difficulties in applying these models to systems that exhibit mixing and/or chaos over a continuous region of space. The work presented here describes a resolution to these issues, in the form of a general analytical mechanism to describe mixing and chaos on continua, that exploits conjugacy to symbolic models that lie outside the traditional purview of symbolic dynamics. This mechanism is then demonstrated on simple, classical models of mixing and/or chaos on continua.

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CP17

Different Routes to Large-Intensity Pulses in Zeeman Laser Model

In this study, we report rich varieties of large-intensity pulses in a Zeeman laser model. The instabilities in the system occurred via three different dynamical processes namely, quasiperiodic intermittency, Pomeau-Manneville intermittency, and breakdown of quasiperiodic motion to chaos followed by interior crisis. This Zeeman laser model is more capable of exploring the major possible types of instabilities when changing a specific system parameter in a particular range. We exemplified distinct dynamical transitions of rare and large-intensity events in the Zeeman laser model. The statistical measures reveal the appearance of the rare probability of large-intensity pulses above the qualifier threshold value, and it follows an exponential decay that shows a Poisson-like distribution. Moreover, the system exhibits irregular swapping between large-intensity pulses and other dynamics near the transition point with the influence of noise.

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CP17

Synchrony and Anti-Synchrony, Applied to Coupled Lorenz Systems

We review the preprint "Invariant Synchrony and Anti-Synchrony Subspaces of Weighted Networks' by Eddie Nijholt, Nandor Sieben, and JWS. We focus on the example of coupled Lorenz equations found in that paper. While synchrony and anti-synchrony of coupled Lorenz equations has been observed for more than two decades, our general analysis of coupled cell networks with linear coupling leads to a deeper understanding of this phenomenon. This allows us to design networks that allow a desired pattern of synchronization and/or anti-synchronization.

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CP17

Restoring the Reciprocity Invariance in Nonlinear Systems with Broken Mirror Symmetry

Reciprocity relations describe invariance properties of elastic wave propagation in materials. In linear, time-invariant materials, reciprocity means that the response of a material

to an external load remains invariant with respect to interchanging the locations of the source and receiver. Avoiding this invariance property has posed a challenge in the design of modern devices for wave engineering. Because mirror-symmetric systems are trivially reciprocal, breaking the mirror symmetry is a necessary requirement for nonreciprocal dynamics to exist in nonlinear systems. In this work, we identify and discuss various operating regimes, bifurcations and manifestations of non-reciprocity in nonlinear materials with broken mirror symmetry. In particular, we discuss response regimes characterized by a nonreciprocal phase shift and report on the existence of stable, steady-state nonlinear reciprocal dynamics in coupled asymmetric systems subject to external harmonic load. We hope that these results contribute to the development of novel materials and devices with unidirectional wave-steering capabilities.

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CP18

Stochastic Resonance in Climate Reddening Increases the Risk of Cyclic Ecosystem Extinction via Phase-Tipping

Human activity is leading to changes in the mean and variability of climatic parameters in most locations around the world. In this work, we demonstrate that changes in climate variability could drive cyclic predator-prey ecosystems to extinction via so-called phase tipping (P-tipping): a nonautonomous instability that occurs only from certain phases of the predator-prey cycle. We use actual climate data from the boreal forest to construct a simple mathematical model of time-varying climate, and couple it to a self-oscillating paradigmatic predator-prey model with realistic parameter values for the Canada lynx and snowshoe hare. In this way, we demonstrate that critically important species in the boreal forest have increased likelihood of P-tipping to extinction under predicted changes in climate variability. Furthermore, our analysis reveals that stochastic resonance is the underlying mechanism for the increased likelihood of P-tipping to extinction.

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CP18

Detecting Long Transients and Regime Shifts in Population Dynamics Data Using Universal Differential Equations

Ecological communities are complex and adaptive, with resulting nonlinear dynamics. Important qualitative features have been observed, such as alternative stable states (bistability where transitions between stable states are caused by perturbations) and long transients (the system resembles an attractor for a long time scale and suddenly shifts its dynamics). These nonlinear dynamics are usually hard to identify using traditional time series analysis methods, and more robust methods usually require a large amount of data, which is not always available for ecological systems. To overcome these challenges, Universal Differential Equations (UDEs) offer a new path forward. UDEs are a novel machine learning approach that predicts the dynamics of a complex system using prior information, i.e. mathematical theory. These priors allow for better predictions with less data requirements. In this presentation we present a proof of concept using UDEs to predict when a transition from a long transient or between alternative stable states occurs in ecological time series. We compare the UDE approach to other machine learning algorithms for time series analysis and to state-of-the-art early warning signal detection algorithms used to detect these transitions in complex systems. The UDE method has the potential to be used to detect these transitions in ecological systems at earlier stages and with less, sparser data, opening up new opportunities for ecological management.

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CP18

Prey-Predator Model of Scomber Colias and Thunnus Thynnus with Presence of with Parasit

In this paper, we develop and study a mathematical model for the dynamics of Scomber colias and Thunnus thynnus prey-predatorwith parasitic helminths. We search to analyze a bioeconomic model in which both susceptible and infected prey populationsScomber colias are exposed to the predator Thunnus thynnus, with varying degrees of exposure. However, the predator feedspreferentially on the most numerous prey types. This implies a kind of switching from the susceptible class to the infected class,and vice versa, as these two types of prey change in numerical superiority. So, the positivity, boundedness, equilibria, stability,and bioeconomic equilibrium are studied. Some numerical simulation of stability is cited. For giving a high yield and keepingthe Scomber colias and Thunnus thynnus populations away from extension, we use the Maximum Principle of Pontryagin.

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CP18

Evolution of Aggression in Consumer-Resource

Models

Are animals in resource-poor environments more or less aggressive than animals in resource-rich environments? Dynamic game-theoretical models provide conflicting answers to this ecological question. We propose a differential equation model that resolves this conflict. In this talk, we explain how the assumptions of a model influence the answer, and we highlight the dynamical behavior of our model.

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CP18

How Realistic Features Affect the Stability of an Arctic Marine Food Web Model

Generalized modeling is applied to explore the impact of various ecosystem characteristics on the overall stability of the Southern Beaufort Sea ecosystem. Incorporating specialized foraging traits of ecosystem members, constraining predatory interactions from habitat modularity, and adjusting predatory weights impacts steady state stability. Stabilizing and destabilizing effects of anticipated changes in species composition due to climate change are discussed. Preliminary results are presented for the collective impact of minor ecosystem members that contribute little to the total biomass on overall stability.

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CP19

Continuation Sheaves in Dynamics: Sheaf Cohomology and Bifurcation

Algebraic structures such as the lattices of attractors, repellers, and Morse representations provide a computable description of global dynamics. In this paper, a sheaf-theoretic approach to their continuation is developed. The algebraic structures are cast into a categorical framework to study their continuation systematically and simultaneously. Sheaves are built from this abstract formulation, which track the algebraic data as systems vary. Sheaf cohomology is computed for several classical bifurcations, demonstrating its ability to detect and classify bifurcations.

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CP19

Elementary Bifurcation Theory and Differentiable Conjugacies

Classic bifurcation theorems describe the local equivalence of bifurcating systems (saddlenode, period-doubling, etc) through topological conjugacies, which is a very weak form of equivalence. At the same time, the impression is often given that the derivation of normal forms is via smooth changes of coordinates (and indeed, this is often true at the bifurcation point itself). So why is it that the equivalence of the (non-hyperbolic) special case appears to be smoother than the (hyperbolic) cases away from the bifurcation? Using the implicit function theorem we show that nonlinear terms of an extended normal form can be chosen so that the local equivalence is differentiable on basins of attraction and basins of repulsion of fixed points or periodic orbits. This means that features such as local convergence rates are preserved. For example, the extended normal form for a saddlenode bifurcation of maps is

$$x_{n+1} = a(\mu) + x_n - x_n^2 + b(\mu)x_n^3,$$

where the coefficients (functions) a and b satisfy simple algebraic equations. The results are illustrated using a continuous time example from climate change modelling.

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CP19

Hopf Bifurcation in a Laminar Pond-Spillway System: Application to Lava Flows During the 2018 Eruption of Kilauea Volcano

During the 2018 Kīlauea lower East Rift Zone eruption, lava from 24 fissures inundated more than 8,000 acres of land, destroying more than 700 structures over three months. After the first month, eruptive activity focused at a single vent (fissure 8, whose cone was later named Ahu'ailā'au) which subsequently fed most of the total erupted lava. For much of this time, the near vent area was characterized by a continuously fed lava pond which was drained by a narrow spillway into a much wider, slower channelized flow. The spillway exhibited intervals of pulsing behavior characterized by the appearance of large stable oscillations in lava depth and velocity with periods of several minutes. At the time this was attributed to variations in vesiculation originating at depth (a direct forcing). Here we construct a simplified fluid dynamical model of these oscillations, positing that the appearance of pulsing is due to a supercritical Hopf bifurcation driven mainly by a slow increase in lava supply from the vent. Asymptotics for the limit cycle near the bifurcation point are derived with averaging methods. The limit cycle periodicity and waveforms predicted by the toy model compare favorably with observations made during the eruption. Intriguingly, these oscillations are made possible in the toy model only by considering the effect of convective accelerations despite the fact that the flow was laminar.

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CP19

Conditions on the Choice of Moment Closures to Preserve Bifurcations in Network Dynamical Systems

Mean-field models of network dynamical systems frequently amount to an exponentially large or even infinite system of coupled ordinary differential equations. Each equation in such a system describes the evolution of a network moment and one frequently observes a hierarchy in which equations for moments of a certain order depend in turn on higher-order ones. To obtain a closed system of tractable size, moment closures are applied to break this hierarchy at some order by approximating all the higher-order moments in terms of lower-order ones. Apart from whether it is quantitatively good, from a dynamical systems' point of view, a key consideration when deriving these approximations has to be whether dynamical features such as bifurcation points remain qualitatively the same. In this talk, we will revisit two paradigmatic network dynamical systems, the SIS epidemic and the adaptive voter model, and derive conditions on moment closure relations that preserve the bifurcations in the closed system.

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CP19

Stepping Down the Thermodynamic Ladder of Chemical Reactions: Do Bifurcations Persist in the Low-Molecule Regime?

In biological practice, Fenichel theory is used extensively to obtain reductions of deterministic models of chemical systems known as quasi-steady-state reductions. The models are systems of nonlinear ordinary differential equations whose solutions describe the time course of biochemical reaction mechanisms. In regard to perturbation problems, Fenichel theory requires the existence of a normally hyperbolic invariant manifold of non-isolated stationary points in the singular limit. It ensures that the normally hyperbolic invariant manifold persists under small and smooth perturbation. We consider a unique perturbation to the irreversible Michaelis Menten reaction where, in the singular limit, the critical set of the layer problem contains a dynamic transcritical bifurcation. Since normal hyperbolicity is lost at the bifurcation point, we show that this problem requires two reductions, one for each attracting submanifold of the critical set. Furthermore, based on the Fenichel reduction, we supplement the classical Gillespie Algorithm with heuristic propensity functions to simplify (reduce) the chemical master equation (CME). Through numerical simulations, we demonstrate that: (1) Our reduced CME is very accurate when the system is sufficiently large; (2) the commonly-accepted Segel-Slemrod condition does not necessarily ensure the reduction of the CME based on the standard Michaelis-Menten equation is accurate.

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CP19

Bifurcations and Dynamics in Inertial Particle Focusing in Curved Ducts

Particles suspended in fluid flow through a curved duct can focus to stable equilibrium positions in the duct cross-section due to the balance of two dominant forces - inertial lift force from axial flow and secondary drag force from cross-sectional vortices. Such particle focusing is exploited in various medical and industrial technologies aimed at separating particles by size. In this talk, I will present results of our numerical investigation of the dynamics of neutrally buoyant particles in fluid flow through curved ducts with rectangular cross-sections. I will show that rich bifurcations take place in the particle equilibria as a function of the duct bend radius. I will also offer insights on how these bifurcations in combination with particle dynamics can be exploited to separate particles of different sizes in circular and spiral ducts.

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CP20

A Dynamical Systems Analysis of Semidefinite Programming with Circulant Semidefinite Matrix

Problem

Positive semidefinite circulant matrices arise in many important applications. This paper construct structured circulant positive semidefinite matrix that is nearest to a given data matrix. The considered approach leads to a dynamical systems analysis of semidefinite programming problem as well as a problem comprising a semidefined program. Some of the numerical issues involved will be addressed including unsymmetrical of the problem. Circulant matrices appear naturally in a variety of applications in mathematics and engineering. The significant applications of circulant matrices have attracted attention of researchers working in different disciplines. Circulant matrices play an important role in investigation of tensor decompositions. Solving many systems requires approximating a data matrix to the nearest circulant positive semi–definite matrix. Sometime because the data matrix is estimated from autocorrelation coefficients is often losses some or all its properties. We present both a method for minimizing a positive semidefinite circulant matrix and we provide an analysis of semidefinite programming from the non-standard though very interesting viewpoint of dynamical systems, Helmke(1994).

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CP20

Dynamical Systems of Cylindrical Origami Tessellation

Recently, origami tessellations, i.e., the folding of crease patterns with repeating symmetry, have attracted much attention as the method to program an object's mechanical properties. We call the folding of origami tessellation uniform if the folding motion of all unit cells, called modules, are identical, and non-uniform if they are not identical. The non-uniform folding of origami tessellations is potentially a great source of non-linear and exotic behaviors; however, it has been challenging to mathematically capture the behavior of non-uniform folding. We propose a novel mathematical model of non-uniform folding, dynamical system of origami tessellation. In this model, we represent the coupled motion of neighboring modules as a discrete dynamical system by providing a recurrence relation from one module to the other using the rigid origami kinematics. In this presentation, we first analyze the 2D dynamical system of a family of cylindrical origami tessellation called waterbomb tube. We show that a waterbomb tube can form a wavy surface that can independently change its amplitude and phase. We also show how the existence of the wavy configuration depends on its crease pattern parameters. In addition, we prove that the dynamical system of a wider family of cylindrical origami is symplectic using area-preserving parameterization. We also discuss the cases of crease-pattern with scaling and higher dimensional systems and show the conservative nature can vanish in some cases.

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CP20

A New Spin on the Classic Rolling Coin Problem

An interesting dynamic response has been observed when a hollow cylinder, initially at rest and laying on its side, is given a transverse velocity in conjunction with axial backspin. For example, lightly pinching a 16oz plastic cup between your foot and the floor, such that is slips out with forward velocity as well as backspin. During the rolling with slip phase, the cylinder pivots up around 45 while simultaneously rotating 180 about an axis normal to the floor. It then transitions to roll without slip where it tracks slight arc while remaining on edge at about 45. While not a particularly applicable observation, this behavior does make for an interesting and demonstrative example for upper-level courses on three-dimensional dynamics. The goal of this paper is to demonstrate how the Moving Frame Method (MFM) can be employed to determine the equations of motion for this behavior, which are then numerically integrated via a time-stepper to animate the simulated response. The MFM is showing pedagogical promise as a systematic approach to 3D dynamics, as the response of the classic rolling coin problem, this sliding cup, Eulers disk, and even a rattleback, can all be found using essentially the same methodical steps. The vector notation of the MFM makes it convenient to use symbolic mathematics software to compute derivatives and cross-products, such that class time can be spent focusing on concepts rather than being bogged down in algebra.

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CP20

Using Modeling and Simulation to Understand Problem Solving with Multiple Solution Methods

A key challenge of education in mathematics and computation is developing students' ability to solve problems that have multiple solution paths. In order to accomplish this, the process of solving these moderately- and ill-structured problems needs to be better understood. We used two approaches to achieve this. First, we performed an experiment in which 72 undergraduate and graduate students solved a problem with multiple solution methods. We found that students who used more than one method tended to perform better than average, suggesting the existence of an optimal number of methods. To investigate this further, we built a mathematical model to describe the behavior of a problem solver with multiple methods at their disposal. Each solution method was modeled with a solve time t_i, and the problem solver may switch between methods. We present two versions of the model: using Markov and Poisson processes to describe the method transition behavior. Two optimization problems are presented: one whose objective is to maximize the solve probability P_{solve} given time limit t_f, and one whose objective is to minimize the solve time t_{solve} to achieve $P_{solve} = 1$. We give analytic solutions for P_{solve} and t_{solve} for the case with two methods. We also present conditions for which switching methods is beneficial. These results are then used to develop a framework of strategies for teaching students to solve problems with multiple solution methods.

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CP20

A Probabilistic Approach to Vanishing Viscosity for Pdes on the Wasserstein Space

In this work we prove an analogue, for partial differential equations on the space of probability measures, of the classical vanishing viscosity result known for equations on the Euclidean space. Our result allows in particular to show that the value function arising in various problems of classical mechanics and games can be obtained as the limiting case of second order PDEs. The method of proof builds on stochastic analysis arguments and allows for instance to prove a Freindlin-Wentzell large deviation theorem for McKean-Vlasov equations.

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CP20

The Winning Strategies for the Pursuers in a Differential Game with Different Constraints

Lots of works have been devoted to pursuit-evasion differential (PED) games, namely [Leon A. Petrosyan, Differential Pursuit Games, Izdat. Leningrad. Univ., Leningrad, 1977], [Mehdi Salimi, Massimiliano Ferrara (2019): Differential game of optimal pursuit of one evader by many pursuers, International Journal of Game Theory, 48 (2), 481-490]. In this research, we first investigate a PED game with one evader and infinite number of pursuers in Hilbert space l_2. The control functions of all players are subjected to the geometric and integral constraint. Evader can escape from all the pursuers if there exists a strategy of the evader such that geometric point of the evader and pursuers are different at any time for any admissible controls of the pursuers. We make a strategy for the evader that ensures scaping it from all pursuers. In the second part of the research, we introduce a winning strategy for the pursuers. This work has application in the robotic science and mobile games.

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CP21

Using An Energy Balance Model to Predict When the Arctic Ocean Will Have Its First Ice-Free Summer

Arctic sea ice is an early indicator of climate change. The rate at which its extent decreases or increases is crucial to monitor closely because Arctic sea ice affects the entire planets physical landscape, through weather patterns, local and global ecosystems, and ocean circulations. Recently, the annual average Arctic sea ice area reached its lowest level since at least 1850 and late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years. The most current report by the Intergovernmental Panel on Climate Change (IPCC) noted the loss of sea ice is mostly driven by the increase of atmospheric greenhouse gasses, unequivocally caused by human activity. Similar studies resulted in strong correlations between the loss in Arctic sea ice and the increase in global mean temperature, CO_2 concentration in the atmosphere, and cumulative anthropogenic CO_2 emissions. In this presentation, I will discuss the development of a model of the Arctic sea ice using an Energy Balance Model (EBM) and expanding on the work of Dr. Somyi Baek, with the goal of refining the prediction for the first ice-free Arctic summer. The most current complex models used by the IPCC predict the Arctic ocean will have its first ice free summer by September 2050. The goal is to discuss how a prominent minimal-complexity model can produce similar results while maintaining its analyzablility.

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CP21

The Effect of Plastic Flow on Glacier Dynamics in a Dynamical System Model for Ice Ages

The KCG [Kallen, Crafoord Ghil, (1979)] conceptual climate model is a nonlinear DE system which describes the interaction between globally averaged temperature and latitudinal glacier extent. It can be shown to admit the existence of stable periodic solutions in the absence of time-dependent insolation forcing. A key assumption in the reduced model is that the creep law describing glacier flow (strain rate proportional to shear stress to power n) is assumed to be perfectly plastic (limit of infinite n) which reduces the glacier geometry to a parabolic profile [Weertman (1964,1976)]. We revisit the glacier flow model by considering the creep law with realistic creep exponent of finite n. The equilibrium glacier shape and glacier dynamics obtained for finite n have significant differences from the perfect plasticity case. In particular, the steady state glacier shape is determined by a piecewise curve dependent on the creep exponent n and contains a dependence on both surface accumulation and melting. Nonetheless, we show from direct simulation of the PDE for ice sheet dynamics that the ice extent can be described by a first order DE. We then contrast the effect of the creep law exponent for typical ice flow ($n \sim 3$) to the perfectly plastic case ($n \to \infty$) on the prediction of time-periodic oscillations in the coupled dynamical system for ice extent and global temperature.

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CP21

Atmospheric Transport Structures Tied to the 'Godzilla' Dust Storm

Every year, dust from the Sahara is transported across the Atlantic through the atmosphere and is deposited in the Caribbean basin and parts of the Americas. On average, it is estimated that 180 million metric tons are transported each year. When conditions are right, large amounts of dust can be emitted from the Sahara and transported across the Atlantic resulting in poor air quality in the impacted regions, the transport of unwanted pathogens that would normally be killed off by UV radiation, and a host of other ecological concerns. Of these events, the so-called 'Godzilla' dust intrusion of June 2020 was the largest and most impactful in the last two decades. By computing Finite Time Lyapunov Exponent (FTLE) fields, we uncover dominant, organizing structures responsible for the evolution of the dust plume as it traverses the atmosphere over the Atlantic. In addition, we identify regions of high hyperbolicity leading to drastic changes in the shape of the plume and its eventual splitting. Coupling this transport modeling with microbiological analysis could assist in understanding similar past events and mitigating possible negative effects of future ones as well.

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CP21

Solving 2-Dimensional Moving Habitat Models with a Hybrid Finite Element Method

Moving-habitat models describe a species dynamics over a climate-driven shifting habitat. They lend insight into the mechanisms promoting a species persistence in the face of climate change. In our approach, reaction-diffusion equations track the species density in time over the whole space. The suitable habitat, defined by a positive intrinsic growth rate, is bounded by a closed curve, called the interface, which shifts in time. Across the interface, there is a jump in density resulting from the consideration of habitat-dependent dispersal rates and habitat bias. Such a system motivates the development of a numerical method that can capture a jump in density across a moving interface. We introduce a mixed weak formulation for this system, where a dual variable acts as a Lagrange multiplier. For this problem, we construct a finite element method. We prove well-posedness for continuous and discrete cases. For the no-shift case, we derive a priori error estimates for the primal variable and compare them with numerical experiments. In the case of a nonzero shift, validated solutions in the 1-dimensional system are available. With a 2-dimensional analogue, we validate our numerical solutions against the previously validated solutions for a wide set of parameter values. We demonstrate the power of the numerical method in application to moving-habitat models by studying the effect of geometry and width on a species' persistence ability.

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CP21

A KinematicDynamic 3D Model for Density-Driven Ocean Flows: Construction, Global Well-Posedness, and Dynamics

Differential buoyancy sources over the ocean induce a density-driven flow that joins faster flow components to create a multi-scale, 3D flow. Temperature and salinity are active tracers that determine the oceans density. We present a robust framework to study effects of a 3D flow on a density-driven component through tracer transport. The model contains an incompressible velocity that couples two advectiondiffusion equations for the tracers. Instead of solving Navier-Stokes, the flow is composed of several modes, one modeling the density-driven flow with a strength that is determined dynamically by averaged density differences, and the other modes completely predetermined. The resulting hybrid kinematicdynamic model is formulated as a nonlinear, weakly coupled, non-local PDE system. We prove its well-posedness in the sense of Hadamard and obtain a priori rigorous bounds. When the relevant Rayleigh number is small enough, we show, rigorously and numerically, that for all initial conditions, the corresponding solutions converge to a unique steady state. Motivated by the Atlantic Meridional Overturning Circulation, the models relevance to oceanic systems is demonstrated numerically. We show that in one limit the model recovers a simplified oceanic box model, including a bistable regime, and in another limit a kinematic model of chaotic advection, suggesting it can be utilized to study spatially dependent feedback processes in the ocean.

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CP22

Symbolic Regression via Neural Networks

Identifying governing equations for a dynamical system is a topic of critical interest across an array of disciplines, from mathematics to engineering to biology. Machine learning - specifically deep learning - techniques have shown their capabilities in approximating dynamics from data, but a shortcoming of traditional deep learning is that there is little insight into the underlying mapping beyond its numerical output for a given input. This limits their utility in analysis beyond simple prediction. Simultaneously, a number of symbolic regression strategies exist, but most either require some intuition or insight about the system, or are susceptible to overfitting or a lack of parsimony. Here we present a new approach that combines the flexibility and accuracy of deep learning approaches with the utility of symbolic solutions: a deep neural network that generates a symbolic expression for the governing equations. We first describe the architecture for our model, then show the accuracy of our algorithm across a range of classical dynamical systems.

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CP22

Analysis of Mean-Field Approximation for Deffuant Opinion Dynamics on Networks

The DeffuantWeisbuch (DW) model is a bounded-confidence type model of opinion formation in which an individuals opinion is influenced only by interactions with agents whose opinions lie within a distance of the confidence bound parameter from the individuals own opinion. The size of the confidence bound parameter is known to strongly affect the number and locations of opinion clusters which form in the infinite time limit solution. Mean-field approximations derived for the model allow mathematical analysis and have been developed for both fully-mixed populations and the case where individuals interact only along the edges of a network. In this work, we present a mathematical analysis of the mean-field DW model on networks composed of two degree classes as well as a fully-mixed population case. With the use of asymptotic analysis, we explain how opinions evolve on such networks and how opinion clusters form. We consider the limit in which the confidence bound is small and derive an approximate model independent of the confidence bound parameter. With linear stability analysis, we also estimate the number and positions of final opinion clusters for any given value of the confidence bound. Comparison with numerical simulations shows that our estimate accurately predicts the location of major clusters for both the network-based model and the model with a fully-mixed population.

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CP22

Dynamics and Applications of Multifunctional Reservoir Computers

In the pursuit of developing artificially intelligent systems there is much to be gained from dually integrating further physiological features of biological neural networks and knowledge of dynamical systems into machine learning environments. In this talk such a two-armed approach is employed in order to translate 'multifunctionality' from biological to artificial neural networks via the reservoir computing machine learning paradigm. Multifunctionality describes the ability of a single neural network that exploits a form of multistability to perform a multitude of mutually exclusive tasks. The dynamics of multifunctional RCs are assessed across several tasks and from this many new application areas are explored which include, data-driven modelling of multistability, generating chaotic itinerancy for memory recall, and reconstructing dynamical transitions present in the epileptic brain.

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CP22

Autocatalytic Networks in the Classroom

This study integrates empirical investigation and dynamical systems modeling to explore the emergence, structure, and evolution of cooperation networks in the classroom. Through analysis and modeling based on longitudinal data collected using surveys, we discovered that (1) student mutual help networks emerge and grow over time; (2) a students position in the network correlates with their individual learning outcomes; and (3) a simple autocatalytic networks model predicts such emergence and correlation. These findings may help improve teaching and learning and provide insight on the origins of synergy.

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CP22

Classification of Lattices of Balanced Colorings of Networks

We consider robust patterns of synchrony (clusters) of a network, which are purely determined by the network structure. Such a cluster is determined by finding a balanced coloring of the nodes of the network, in which each cluster of nodes receive the same numbers of arrows of each color. Balanced colorings also correspond to subspaces that are flow-invariant for all admissible ODEs. We represent all possible such patterns of synchrony as a complete lattice by using hierarchy structure of partition of nodes. We classify lattice structures using the Jordan normal forms of the adjacency matrices of networks. We also show that assigning a well-defined non-negative integer index to a lattice leads to synchrony-breaking bifurcation analysis of networks.

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CP22

The Low-Rank Hypothesis of Complex Systems: From Empirical and Theoretical Evidence to the Emergence of Higher-Order Interactions

Behind the blur caused by the high-dimensional nonlinear dynamics and the intricate organization that charac-

terize complex systems, hide essential mechanisms that explain the emergence of macroscopic phenomena. To identify those mechanisms, it has been common practice for researchers to model complex systems using dynamics that depend upon low-rank matrices, without any justification for choosing such simple matrices to draw conclusions about complicated problems—what we call the low-rank hypothesis [Thibeault et al., "The low-rank hypothesis of complex systems', arXiv, 2022]. We identify three indicators of the low-rank hypothesis and expose its ubiquity among the random network models studied in various fields of study, ranging from spin glasses and machine learning to neuroscience. Notably, we formulate a theorem in spectral graph theory proving that the soft configuration model satisfies the hypothesis and we verify the hypothesis experimentally for more than 600 real networks of various origins. We then reveal the major repercussions of the low-rank hypothesis on nonlinear dynamics. In particular, we show that the validity of the low-rank hypothesis gives grounds to the idea of reducing the dimension of complex systems. We finally prove that higher-order interactions emerge naturally from an optimal dimension reduction, which demonstrates the profound interplay between the description dimension of a system and the possibility of having higher-order interactions.

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CP23

Controllability of Impulsive Semilinear Differential Equations.

This talk deals with sufficient conditions for the approximate controllability of impulsive semilinear control systems. We have considered two different sets of sufficient conditions. In the first set, we derived the results by applying the theories related to the compactness of semigroup and Schauder's fixed point theorem. In the second set, we derived the results by applying Gronwall's inequality and avoiding the use of the fixed point theorem and compactness of semigroup.

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CP23

Modeling and Sensorimotor Control Strategies for Octopus Arms – An Overview

In this talk, we aim to provide a broad overview of modeling and various control strategies for a soft octopus arm. Octopus arms are muscular hydrostats with virtually infinite degrees of freedom. This endows the arms with extreme flexibility and unique manipulation capabilities in unstructured environments. The intricate interplay between the peripheral nervous system (PNS) and the continuum biomechanics of the arm musculature, on the other hand, poses significant control challenges. To address these issues, we first present a Cosserat rod model of a flexible arm, where the interaction between PNS and musculature is also modeled to effectively exert internal loads (forces/couples) on the arm. Given our model, we will then proceed to describe several control strategies that explain several biophysical experimental observations. Among various observed stereotypical arm movement patterns, bend propagation seems to be the most prominent one, where octopuses create a bend near the base of the arm and propagate the bend along the arm by traveling waves of muscle actuation. The mechanisms (sensorimotor control) behind such maneuvers remain unsolved. We investigated the bend propagation phenomenon using reduced-order modeling, sensory feedback control, and neuromuscular control approaches. Our findings not only explain octopus arm control but also provide directions for controlling soft robotic manipulators efficiently.

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CP23

Bilinear Control of Fluid Flows Governed by Data-Driven Bilinear Reduced Order Model

Recent research on data driven isostable-based reduced order dynamical models aids in explaining model dynamics as compared to full order models. In order to capture the dynamics of observables in a computational model for fluid flow over an airfoil, a bilinear extension of isostable coordinate-based data-driven model is proposed here. This reduced order model replicates the dynamics' even better since it incorporates nonlinearity within the bilinear model. Flow control has been achieved in this model utilizing bilinear control with lift as the observables. Reduced order model exhibits identical behavior as full order models for flow control and bilinear control outperforms linear control, indicating that it can be expanded even further for realistic fluid flow models.

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CP23

Stabilization and Adaptive Event-Triggered Tracking Control for Fuzzy Model-Based Neutral-Type Dynamical Systems

An adaptive event-triggered output tracking problem for neutral-type dynamical systems with malicious attacks and disturbances is discussed in this work. The interval type-2 fuzzy approach is used to linearize the non-linear systems with weighted membership functions. An adaptive event-triggered mechanism is developed to reduce the number of triggering and communication burdens. Feedback control is constructed to force the output trajectories to track reference input signals even in the presence of disturbances and malicious attacks. The tracking objective transformed into an input-output finite-time stabilization problem for the considered neutral-type dynamical system. The required sufficient conditions are developed in the structure of linear matrix inequalities based on LyapunovKrasovskii functional and some advanced integral inequalities. Finally, the proposed methodology is applied to engineering models to validate the efficiency and applicability.

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CP23

Hybrid-Trigger Based Disturbance Rejection Control for Repeated Scalar Nonlinear System

In this work, the stabilization and active disturbance rejection problem for repeated scalar nonlinear system is discussed. In order to stabilize and reduce the communication burden, hybrid-triggered based feedback control is proposed for the considered system. Further, an improved equivalent input disturbance estimate technique is incorporated to the feedback control to suppress the effects of external disturbances. To be more specific, a Bernoulli distributed stochastic variable describes the switching rule of data transmission. As a result, high accuracy estimations of the unexpected disturbance signals are established on the basis of the proposed control scheme. In the context of linear matrix inequalities, a set of essential conditions are developed by applying Lyapunov stability theory to ensure the system is mean-square asymptotic stable. Numerical examples with engineering significance are demonstrated to emphasize the advantages of the proposed control technique.

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CP23

Optimal Sampling, Communication, and Distributed Control Protocols via Pseudo-Spectral Methods

Large-size structures and systems, implemented as cyber-physical systems (CPS), are prevalent across diverse domains, e.g., power grids. In these systems, computing, communication, and control components are integrated with physical systems into a single distributed platform. The increased capability of CPS has a concomitant stipulation as they demand significant additional resources for enabling coordination and control under communication and computation constraints. In this work, we develop sampling and communication strategies to optimize the communication and computational resources in a purely data-driven cyber-physical control system. We develop these protocols in conjunction with the learning schemes by employing the pseudo-spectral method, where we design the sampling and communication protocols simultaneously by employing Chebyshev nodes together with the Chebyshev polynomials. Our idea is to use these nodes as the sample points in the domain of the unknown function and generate minimal data at these sample points for learning optimal control policies and dynamics, e.g., the drift- or control-vector fields. Given the data samples at these nodes, our sampling and communication policies will enable learning with quantifiable accuracy to realize data-driven filters and controllers. The resulting approximations of the control policies and dynamics are close to the best polynomial approximation in their domain under the maximum norm in the interval of approximation.

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CP24

The Non-Linear Nature of the Resilience of Social Organisations

Social organisations form non-equilibrium social structures characterised by a volatile dynamics. Individuals join or leave. Social relations change quickly. In this presentation, we clarify why existing resilience concepts cannot provide a comparable, quantifiable insight into the resilience of such systems. They largely miss the coupling between structure and dynamics, expressed in the nonlinear relation between *robustness*, the ability to withstand a shock, and *adaptivity*, the ability to respond to shocks. Instead, they treat these dimensions as independent or, more often, only focus on robustness and stability. So, how does the resilience of social organisations depend on their robustness and adaptivity? We propose a novel resilience measure combining these quantities and further demonstrate how they can be quantified using data from a software developers collective. Our analysis reveals a **resilience life cycle**: stages of increasing resilience are followed by decreasing resilience. We explain the reasons for these observed dynamics and provide a formal model to reproduce them. The resilience life cycle allows distinguishing between short-term resilience, given by a sequence of resilient states, and long-term resilience, which requires social organisations to survive through different cycles.

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CP24

The Perils Of Political Centrism

In this talk I will present a model of two competing political candidates who shift views opportunistically to maximize their share of the vote. We start with some observations about the model. First, the best strategy for a candidate is often to move towards the other candidate, eventually resulting in two centrists with coalescing views. Second, this strategy ceases to be optimal as soon as sufficiently many voters respond to their candidates opportunistic drift towards the center by staying away from the polls altogether. The surprise is that the change in the optimal candidate position can, in certain circumstances, be discontinuous. The underlying mathematical mechanism is a blue-sky bifurcation.

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CP24

Using Mathematical Models to Uncover the Effects of Various Factors That Contribute to Opioid Addiction

In the 2015 National Drug Threat Assessment Summary, the United States Drug Enforcement Administration stated that overdose deaths, particularly from prescription drugs and heroin, have reached epidemic levels. Since this assessment, the situation has continued to deteriorate; exacerbated by the Covid-19 pandemic and increases in the use of heroin and fentanyl. Using publicly available data, we adapt SIR-type compartment models to the opioid crisis to better understand the risks and drivers of addiction. Specifically, we focus on the relationship between time spent taking prescriptions and addiction, the functional response of social contacts on addiction, and the impact of risk factors such as mental health conditions.

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CP24

Efficacy and Neighbourhoods, Or How the Communitys Actions Affect Crime Rates

What if the residents of a neighbourhood could influence crime rates with their behaviour? This is what postulates the theory of collective efficacy. Collective efficacy is the conviction shared by a group of people that they can work together to successfully complete a specific task. The idea is that the difference in neighbourhoods inner structure leads to spatial variation in crime rates. Many models exist that show the negative link between collective efficacy and crime but the literature in studying the formation of patterns is still limited. We present results from the Crime Survey for England and Wales 2007-2010, that shows that collective efficacy clusters in space leading to regions with coherent structure. We then develop a novel convolution model of collective efficacy based on social theories that allows for a mathematical investigation of neighbourhood and resource effects on the formation of collective efficacy and transitions between different regions.

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CP24

Large Population Limits of Markov Processes on Random Networks

We consider time-continuous Markovian discrete-state dynamics on random networks of interacting agents and study the large population limit. Typical applications include social dynamics (e.g., opinion spreading) and epidemiology (e.g., SIR models). The dynamics are projected onto low-dimensional collective variables given by the shares of each discrete state in the system, or in certain subsystems. In the example of an SIR model, the collective variable would be given by the percentage of susceptible, infectious, and recovered nodes. We provide general conditions for the convergence of the collective variable dynamics to a mean-field ordinary differential equation. Finally, we discuss the convergence to this mean-field limit for a continuous-time noisy version of the so-called ”voter model” on Erds-Rnyi random graphs, on the stochastic block model, and on random regular graphs. The talk outlines the results presented in the preprint [Lcke et al., 2022, arXiv:2210.02934] with identical title.

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CP25

Can Strange Sets Arise Out of Quantum Dynamics?

Strange attractors are routinely observed in classical chaotic systems. The classical forced impact oscillator is known to undergo a sudden transition to chaos when the mass grazes the wall. We numerically investigate the equivalent quantum system which shows aperiodic evolution of the wavefunction. The entropy of the probability density and the L1-norm are used to generate real-valued time series, which reveal the character of the dynamics. The sinusoidally forced quantum system exhibits a novel form of dynamics characterized by an explosion in the number of frequency components, and the dense set of discrete peaks implies a strange orbit. We observe no sensitive dependence on initial condition. Both the 01 test for chaos and the modified 01 test, yield values between 0 and 1, divulging the presence of strange nonchaotic dynamics. Such dynamics, characterized by being aperiodic, but not chaotic in the Lyapunov sense, is commonly observed in quasiperiodically forced classical systems. The underlying attractor in such systems is fractal. The distribution of finite-time Lyapunov exponents has positive components, also indicating a strange set. One noticeable feature is that the spectral distribution function has an exponential character instead of a power-law character as has been reported earlier for strange nonchaotic attractor.

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CP25

Pinning in An Extended Lugiato-Lefever Model

In applications, locking of the repetition rate of a Kerr soliton comb inside a microresonator by pumping two modes is of particular interest. Mathematically this can be described by a new variation of the Lugiato-Lefever equation (LLE) given by

$$\mathrm{i}u_t = -du_{xx} + \mathrm{i}V(x)u_x + (\zeta - \mathrm{i})u - |u|^2 u + \mathrm{i}f,$$

which is a damped and driven nonlinear Schrdinger equation with an additional potential $V(x)$. In the first part we discuss the existence of nontrivial stationary 2π-periodic solutions of the LLE using bifurcation theory and show that localized solitons can be found if the potential $V(x)$ has a sign change. In the second part we discuss stability properties of these solutions and show numerical simulations with `pde2path` that complement our analytical findings.

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CP25

Towards Optimal Design with Maxwell's Equations and Hmm

We are interested in designing materials that have unique electromagnetic properties, for example, a material that does not absorb 5G signals. Electromagnetic waves like 5G signals are governed by a set of partial differential equations called Maxwell's equations. To describe the interaction of electromagnetic waves with materials, we couple Maxwell's equations with constitutive laws like the Lorentz model and LandauLifshitz model. However, materials with such unique electromagnetic properties often have nanoscale structures. It poses a challenge to solve the particular solutions for Maxwell's equations numerically due to the computational cost. A numerical method for simulating Maxwells equations coupled with Heterogeneous Multiscale Methods for the constitutive laws will be presented.

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CP25

Continuum Limit of $\mathbb{R}^{2+1}$ Nonlinear Schrödinger Equation

Recently, there has been an increased interest in non-local PDEs. While most of the research deals with continuum models, less is known about discrete systems showing global coupling with algebraic decay on the coupling strength. This work considers such a case in a two-dimensional lattice and centers on the question of the validity of a suitable continuum approximation. We prove that the solutions to the discrete Nonlinear Schröodinger Equation (DNLSE) with non-local algebraically-decaying coupling converge strongly in $L^2(\mathbb{R}^2)$ to those of the continuum fractional Nonlinear Schrödinger Equation (FNLSE), as the discretization parameter tends to zero. The proof relies on sharp dispersive estimates that yield Strichartz estimates that are uniform in the discretization parameter. An explicit computation of the leading term of the oscillatory integral asymptotics is used to show that the best constants of a family of dispersive estimates blow up as the non-locality parameter $a?(1, 2)$ approaches the boundaries. In particular, the temporal decay of $O(t^{-d/3})$ for the classical Schrödinger evolution is not recovered by taking the left one-sided limit as $\alpha \to 2$.

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CP25

Three Pieces Riemann Problem for 2-D Full Euler System in the Noble-Abel Gas

We present Riemann problem governed by 2-D full Euler system in the Noble-Abel gas. Riemann data, consisting three constants, are distributed in three distinct regions with an assumption that two adjoining regions can be connected by only one planar elementary wave. We present criteria for existence of different configurations of elementary waves for isentropic, as well as full, Euler system. We also discuss the effect of the Noble-Abel gas and the angle of regions on elementary waves and corresponding stream curves.

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CP25

Simulating Antimatter Gravity

The assumption that the effects of gravity on antimatter and matter are equivalent has permeated throughout almost all of modern physical theory and experiment. However, no direct observation of this effect from gravity has been made on a particle in freefall. A muonium beam diffracting through a series of gratings has proven to be a suitable method for recording such freefall. Simulating this with the best current understanding of diffraction and interferometry is vital in determining this antimatter-gravity relationship, since a physical construction requires a picometer-precise atom interferometer and muonium beam. The development of these simulations has both demonstrated the relative feasibility of experimentation and brought to question the viability in applying certain physical modeling and simulation methods.

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CP26

Equilibria and Dynamics of Altitudinal Magnetic Rotors on a Circle

Macroscopic magnets can easily be manipulated and positioned so the interactions between themselves and with external fields induce interesting dynamics and equilibrium configurations. In this work, we use rotating magnets positioned in a line or at the vertices of a regular polygon. The rotation planes of the magnets can be modified at will. The rich structure of stable and unstable configurations is dictated by the symmetry and the separation between the magnets. As we show both symmetric solutions and their symmetry-breaking bifurcations can be explained by group theory. Our results [for instance Mellado, Concha, Mahadevan, Phys. Rev. Lett. 109, 257203 (2012); Concha, Aguayo, Mellado, Phys. Rev. Lett. 120, 157202 (2018); Cisternas et al. Physical Review B 103, 134443 (2021)] revisit several themes of dynamical systems such as basins of attraction, fractals, spectra with self-similar features, optimal control, the motion of domain walls, and Walker breakdown. Our analyses indicate that these beautiful phenomena should emerge at any length scale, in particular the size of commercially available neodymium magnets.

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CP26

Macroscopic Interpretations of Microscopic Car-Following Models with Traffic Waves and Sparse Controls

Various car-following models, such as the Intelligent Driver Model (IDM), can reproduce instabilities and traffic waves that are observed in real traffic flow. Low density autonomous vehicles (AVs), acting as Lagrangian flow actuators, have the potential to dampen and prevent these undesirable non-equilibrium phenomena. By connecting traffic models from micro to macro scales, we outline some of the key macroscopic flow consequences of microscopic traffic waves, of AV-based flow smoothing, and of the effects on the overall system-level energy consumption balance.

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CP26

Research and Experimentation on the I-24 Motion Testbed

We describe the I-24 MOTION open road testbed led by the Tennessee Department of Transportation on Interstate 24 near Nashville, TN. The purpose of the testbed is to provide an open road experimental facility for testing traffic management and automated vehicle technologies in real freeway traffic. During normal operation of the testbed, it also provides an unprecedented amount of anonymized vehicle trajectory data that can be used to unlock new traffic science, safety improvements, and driver modeling. The testbed consists of pole-mounted 4K resolution video cameras providing uninterrupted coverage of the roadway. Video data is processed in real time into vehicle trajectories for all vehicles passing through the testbed. The length of the testbed will be 4 miles in 2022, with plans to expand to 6 miles. The testbed will capture and visualize the trajectory data of daily traffic flow. In November 2023, the CIRCLES consortium will run a large scale experiment to take advantage of this testbed. This is the first connected and automated vehicle experiment to be run on I-24 MOTION: 100 vehicles are deployed to the highway with enhanced cruise control algorithms specially designed for dampening phantom traffic waves and improving the stability and energy consumption of the traffic stream.

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CP26

Controlling the Fractional Reaction Diffusion Equation

This work present the control of a fractional reaction diffusion equation. This equation, contains a fractional derivative in space and time. The solution of this equation tend to explode per large time. So we propose a modification of the equation to control this solution's explosion. We also present some necessary conditions for the stability and instability of the equations. Finally, we give some numerical tests that prove what we confirm.

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CP26

Neural Network-Based State Estimation of Lithium-Ion Batteries Under Internal Faults

Intelligent battery management systems with advanced estimation algorithms are critical for health-conscious decision-making and the safe operation of lithium-ion (Li-ion) batteries. In this research, we propose a neural network (NN)-based state-of-charge (SOC), state-of-health (SOH), and core temperature estimation schemes in the presence of an internal fault. First, we develop a model-based fault detection scheme using a SOH-coupled electro-thermal-aging model (ETA) integrated with the ohmic resistance dynamics. We then develop a nonlinear observer to generate the fault detection residuals using surface temperature, terminal voltage, and current measurements. In contrast to the traditional constant threshold-based fault detection approaches, which cannot be employed in the case of the Li-ion battery due to accelerated degradation and change in parameters, in our approach, we use an adaptive threshold that accounts for these uncertainties. Upon detection of a fault, we introduce a second NN-based observer to learn the fault dynamics and estimate the battery's SOC, SOH, and core temperature. The NN weight training algorithm uses the estimated healthy states and measured outputs to address the challenge of fewer output

measurements from the battery. We also prove the convergence of the observer's state and weight estimation errors using the Lyapunov theory and corroborate the analytical results with numerical simulation and experimental results.

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CP27

Green's Law and the Riemann Problem for Waves in Inhomogeneous Media

The propagation of long waves onto a continental shelf is of great interest in tsunami modeling, where understanding the amplification of waves during shoaling is of significant importance. This talk revolves around an apparent paradox surrounding the amplitude of a wave that has travelled through a medium. Resolving this paradox reveals a connection between Green's law and the Riemann problem. This enables us to find a new way to find solutions of waves in non-homogeneous media. Ocean waves will be the main case highlighted but it applies to all sorts of waves (light, acoustic, seismic).

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CP27

Phase Space Analysis of Nonlinear Wave Propagation in a Bistable Mechanical Metamaterial with a Defect

We study the dynamics of solitary waves traveling in a one-dimensional chain of bistable elements in the presence of a local inhomogeneity ('defect). Numerical simulations reveal that depending upon its initial speed, an incoming solitary wave can get transmitted, captured or reflected upon interaction with the defect. The dynamics are dominated by energy exchange between the wave and a breather mode localized at the defect. We derive a reduced order two degree of freedom Hamiltonian model for wave-breather interaction, and analyze it using dynamical systems techniques. Lobe dynamics analysis reveals the fine structure of phase space that leads to the complicated dynamics in this system. This work is a step towards developing a rational approach to defect engineering for manipulating nonlinear waves in mechanical metamaterials.

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CP27

Diffusion-Driven Instability of Topological Signals Coupled by the Dirac Operator

The study of reaction-diffusion systems on networks is of paramount relevance for the understanding of nonlinear processes in systems where the topology is intrinsically discrete, such as the brain. Until now reaction-diffusion systems have been studied only when species are defined on the nodes of a network. However, in a number of real systems including the brain and the climate, dynamical variables are not only defined on nodes but also on links, triangles and higher-dimensional simplices, leading to topological signals. In this work we studied reaction-diffusion processes of topological signals coupled through the Dirac operator, which allows topological signals of different dimension to interact or cross-diffuse as it projects the topological signals defined on simplices of a given dimension to simplices of one dimension up or one dimension down. In such framework, signals on a 0-simplex are coupled with the projection of signals in the 1-simplex and they diffuse through the Hodge Laplacian of order 0, and so on for higher dimensions. By focusing on the framework involving nodes and links we establish the conditions for the emergence of Turing patterns and we show that the latter are never localized only on nodes or only on links of the network. Moreover when the topological signals display Turing pattern their projection does as well. We validated the theory on a benchmark network model and on square lattices with periodic boundary conditions.

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CP27

System Matrix Classification in Layered Media Impact Problems

In this work, we classify the matrix representing a discrete dynamical system, previously developed for an impact problem in Goupillaud-type layered elastic media. A Goupillaud-type layered medium is characterized by equal wave travel time in each layer. As the stress wave propagates back and forth, the composition of the layered medium effects the system matrix entries. While preserving the property of each row summing to one, some of the matrix entries can be negative. We identify in the physical context of Goupillaud-type media, conditions that lead to Markov, Positive Markov, Regular Markov matrix and beyond. Our analytical results are supported by numerical experiments. Besides convergence implications for the stress terms, this works further contributes to applications of Markov matrices in wave propagation in layered media.

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CP28

Analysis of Latent States Modeling of Biological Systems Using Hybrid Differential Equation Recurrent Neural Network Models

Physiological dynamic models are often represented using a system of ordinary differential equations (ODEs). The system of ODEs modeling a dynamic system frequently relies on measurements from multiple nodes. In realistic biological systems, it might not be possible to measure these nodes for a variety of reasons. Incorporating latent states in the model helps to compensate for the lack of measurements in such cases. In this talk, we utilize cubature Kalman filters and recursive Bayesian state estimation with a hybrid ODE-Neural Network model to approximate the output of missing ODEs and measurements. We apply this approach to two models of biological systems: a model of compartmental pressures in the human retina and the Hodgkin-Huxley model for neuron action potentials. Both of these models include states which cannot be readily measured, and we demonstrate how our approach can produce accurate estimates in spite of this hurdle.

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CP28

Chromatin Remodeling During Cellular Reprogramming: A Data Driven Physics-Based Modeling Approach

Chromatin is dynamically reorganized during aging, disease, and reprogramming. To what extent epigenetic marks influence this reorganization remains an open question. To gain insight into the relationship between epigenetic marks, local chromatin accessibility, and large-scale chromatin organization, we are building a model of chromatin that bridges information from several different experimental modalities, including ChiP-Seq, ATAC-Seq, and Hi-C, with a physics based model of chromatin dynamics. Chromatin is represented as a bead-spring polymer chain, with each bead representing a nucleosome in a particular epigenetic state. We use data from histone-mark targeting ChiP-Seq experiments to determine the epigenetic state of each nucleosome along our polymer. We then define interactions between classes of nucleosomes and perform Brownian dynamics simulations to obtain the trajectory of the system over time. Using these trajectories, we generate synthetic HI-C contact maps and chromatin accessibility profiles, which we can compare to experimental data for refinement and validation. We plan to use this tool in the context of cellular programming and rejuvenation to generate chromatin dynamic trajectories, suggest potential design principles of reprogrammed cells and drive experimental validation of in silico reprogrammed states. Furthermore, this technique allows to simulate trajectories which result from transitions between states.

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CP28

From Spikes to Waves: Organized Stochastic Dynamics in Calcium Signalling

Intracellular Calcium signaling is organized in a hierarchical manner. At the lowest level, stochastic release of through a single IP3 receptor results in a small localized increase in cytoplasmic concentration, which is often termed a 'blip'. The IP3 receptors are typically tightly clustered, which means that a blip can stimulate the release of additional through neighboring receptors, so that the entire cluster emits a localized puff. At the highest level of organization, if enough puffs are generated, they can form a propagating wave of increased across an entire cell. This work develops an accurate microscopic stochastic model of calcium signaling, and then employs statistical mechanical techniques to determine effective macroscopic equations. The model consists of many IP3 channels distributed throughout the cell, each opening and closing stochastically. Calcium and IP3 diffuse throughout the cell, and the local concentration of each of these is affected by the stochastic behavior of the channels. The model is thus of hybrid form: consisting of the discrete stochastic channels coupled to the calcium and IP3 diffusion, which are modelled with PDEs. The probability of enough channels opening for there to be a cell-wide wave is estimated using the theory of large deviations. It facilitates detailed estimates for the probability of rare events, and also a means of determining the most likely trajectory followed by the system in attaining rare events.

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CP28

Individual Based Modeling to Understand Oak Wilt Disease Spread in Minnesota

Mathematical modeling has been successfully used in understanding plant disease spread and dynamics for many years. Many mathematical and statistical tools have been introduced to describe spatial patterns and temporal variance of the plant disease. Oak wilt is caused by the fungus Bretziella fagacearum and is responsible for killing large numbers of oaks every year in Minnesota. The gravity of the oak wilt threat to forest ecosystems makes it very important to understand better how the disease spreads and which variables play an essential role in the dynamics.We use individual- based modeling to understand the transmission and spread of the disease. Individual-based models are a kind of micro-scale model that simulate the simultaneous operations and interactions of multiple individuals in an attempt to re-create and predict the appearance of complex phenomena. We show this simulation model can be another tool to be used by the forest management to track and manage the disease in Minnesota.

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CP28

Information Processing in the Adaptive Immune Response

The adaptive immune system surveils a large distribution of antigens and implements a range of complex multi-cellular outcomes in response. Each antigen is characterized by features encoded in its physical structure and the dynamics of its source pathogen. Although systems immunology has catalogued the molecular interactions mediating the immune response, we lack an understanding of how the response is calibrated to antigen features. Furthermore, as the response is constrained by molecular noise and phenotypic variation in responding cells, it is unclear how the system delivers an appropriate and effective response. Here, using computational and analytic methods, we investigate how the dynamic network of agents antigens, cytokines, nave, effector, memory and regulatory cells processes information about antigen features. We compare the information capacity of many network structures and identify biologically plausible networks that maximize information transmission in the adaptive immune response. A comprehensive understanding of these networks may be critical for the safe and robust application of perturbative immune therapies in cancer and other diseases.

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CP28

Pain Begets More Pain: A Self-Exciting Model for Pain Caused by Sickle Cell Disease

Sickle cell disease is a disorder that affects red blood cells and is associated with chronic pain as well as acute pain crises that often result in hospitalization. Our ongoing study is an effort to better understand pain events in sickle cell patients. We build on the theory of self-exciting point process, specifically Hawkes process, to develop a mathematical model that relies only on patient pain history. Our model is then fitted to data collected from 39 patients at the Duke University Sickle Cell Center and compared to simplistic yet plausible null models.

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CP29

Bifurcations Arising from Nonlinear Interactions and Harvest

Sustainable fisheries are an important source of high–quality protein. Harvesting wild populations reduces the ecosystem services they provide. For species engaged in intraguild predation, common in marine and aquatic ecosystems, reduction of those services compounds losses from harvest, hastening population collapse. We performed bifurcation analyses on a two–species model with intraguild predation and showed that adding constant harvest generates the possibility for five interior co–existence equilibria. We show how varying key parameters and harvest levels generate saddle–node bifurcations and loss of stable equilibria. Similarly, after reparameterizing the model, we show that with harvest, varying ecological parameters can dramatically affect the size of basins of attraction for stable equilibria. At critical parameter values, a subcritical Hopf bifurcation occurs wherein a stable focus appears inside an unstable limit cycle. Reversing this, the limit cycle converges on the focus, and at the critical value, both disappear, leading to catastrophic extinction of the intraguild predator, often the target of harvest. Analysis of nonlinear models generates insights into how ecological complexities interact with harvest to generate undesirable outcomes. Our results reveal which ecological parameters interact most strongly with harvest providing information on how to avoid fisheries collapse when harvest losses are compounded by nonlinear species interactions.

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CP29

Numerical Evidence of the Prevalence of Subcritical Hopf Bifurcations in the FitzHugh-Nagumo Model

It is known that for spiral waves, the transition from rigid rotation (RW) to meander (MRW) is via a Hopf bifurcation. In several models of excitation, this was shown to be a supercritical Hopf bifurcation, but we show numerical evidence of how prevalent subcritical Hopf bifurcations are in the FitzHugh-Nagumo (FHN) model in $\mathbb{R}^2$. In 1991, Winfree published a parametric portrait of FHN which separated regions between no waves, plane waves, rigidly rotating waves, meandering waves and hypermeandering waves. We conducted simulations for the FHN model along the boundary between RW and MRW, known as ∂M in Winfree, 1991. Due to the large core nature of these waves as they reach the ∂M boundary, we conducted simulations in a comoving frame of reference (Foulkes & Biktashev, 2010; Sehgal & Foulkes, 2020), allowing us to conduct simulations in smaller box sizes but still generating the features needed to study the dynamics of the waves. Measuring the size of the underlying limit cycles of the meandering waves, we show that the entirety of the upper part of the ∂M boundary (going from RW to MRW as we increase β) has hysteretic features and providing evidence of subcritical Hopf bifurcations. The lower boundary (transition from MRW to RW as we increase β) has no hysteretic features at all, and the transition from RW to MRW along this boundary is most likely to be supercritical due to the square root growth of the limit cycle.

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CP29

The Three-Dimensional Generalized Hénon Map:

Bifurcations and Attractors

We study dynamics of a generic quadratic diffeomorphism, a 3D generalization of the planar Hénon map. Focusing on the dissipative, orientation preserving case, we give a comprehensive parameter study of codimension-one and two bifurcations. Periodic orbits, born at resonant, Neimark-Sacker bifurcations, give rise to Arnold tongues in parameter space. Aperiodic attractors include invariant circles and chaotic orbits; these are distinguished by rotation number and Lyapunov exponents. Chaotic orbits include Hénon-like and Lorenz-like attractors, which can arise from period-doubling cascades, and those born from the destruction of invariant circles. The latter lie on paraboloids near the local unstable manifold of a fixed point.

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CP29

Spatial Models of Forest-Savanna Bistability

Empirical studies suggest that for vast tracts of land in the tropics, closed-canopy forests and savanna are alternative stable states, a proposition with far-reaching implications in the context of ongoing climate change. Consequently, numerous mathematical models, both spatially implicit and explicit, have been proposed to capture the mechanistic basis of this bistability and quantify the stability of these ecosystems. We present some analysis on a spatially extended version of the so-called Staver-Levin model of forest-savanna dynamics (a system of nonlinear partial integro-differential equations). On a homogeneous domain, we uncover various types of pattern-forming bifurcations in the presence of resource limitation, which we study as a function of the resource constraints and length scales in the problem. On larger (continental) spatial scales, heterogeneity plays a significant role in practice, and incorporating domain heterogeneity leads to interesting phenomena such as front-pinning, complex waves, and extensive multistability, which we investigate analytically and numerically.

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CP29

Bifurcations of Temporal Dissipative Solitons

We present results on the branching of temporally localized, two-pulse periodic traveling waves from one-pulse periodic traveling waves in delay differential equations (DDEs) with large delay. We show numerically and by means of a prototypical example that analogous to traveling pulses in reaction-diffusion partial differential equations the branching of two-pulse TDSs from one-pulse TDSs with non-oscillating tails is organized by codimension-two homoclinic bifurcation points of a real saddle equilibrium in a corresponding traveling wave frame. More specifically, we investigate a generalization of Sandstedes model with an additional time-shift parameter, and use Auto07p and DDE-BIFTOOL to compute numerically the unfolding of codimension-two homoclinic bifurcation points in the resulting DDE. We then interpret this model as the traveling wave equation for TDSs in a DDE with large delay by exploiting the reappearance of periodic solutions in DDEs.

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CP30

Using Weighted Birkhoff Averages to Measure Rate Induced Tipping in Hamiltonian Systems

Rate Induced tipping has been an area of particular interest in noisy systems but recently it has been used for fully deterministic systems. The periodically forced Duffing oscillator subjected to a parameter drift is an example of a Hamiltonian system characterized by tori separated by chaotic seas. While the parameter grows, the chaotic sea grows, absorbing many of the tori. When the rate of the parameter change is slow, many of these tori persist for long periods of time. Computing whether an orbit is chaotic or quasi-periodic is typically a computationally exhaustive task. Using the method of weighted Birkhoff averages, we speed up this process and allow for quicker measurements of tipping probabilities.

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CP30

Modeling the Temporal Evolution of High-Dimensional Densities Using Optimal Transport and Projection Pursuit

We propose an efficient generative model for the temporal evolution of high-dimensional densities based upon optimal transport and projection pursuit. Specifically, we join samples from neighboring snapshots via optimal transport maps and interpolate the evolving density using cubic splines. This approach has three main benefits. First, when the sampling frequency is sufficiently high, the optimal maps closely approximate the identity and are thus cheap to compute. Moreover, the training process is highly parallelizable as all optimal maps are independent of one another and can therefore be learned simultaneously. Finally, the approach is based solely on numerical linear algebra and is therefore simple to analyze. We present several numerical experiments on synthetic datasets to demonstrate the utility of our method for modeling high-dimensional solutions to the Fokker–Planck equation. Through these experiments, we show that the proposed approach is highly competitive with state of the art normalizing flows conditioned on time.

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CP30

A Fast and Scalable Method for Computing Nonlinear Reduced-Order Models Respecting Conserved Quantities

Reduced-order nonlinear solutions (RONS) were developed recently as a powerful method for reduced-order modeling of PDEs. RONS significantly broadens the scope of reduced-order modeling compared to previous projection-based methods, and allows for enforcing conserved quantities of the PDE in the reduced model. In this talk, we will discuss a fast and accurate method for forming the RONS equations. This method exploits the structure of the metric tensor involved in RONS to reduce the computational cost by several orders of magnitude. This speed up allows us to go beyond reduced-order modeling and use RONS for accurate numerical simulation of PDEs. We demonstrate the application of the proposed method on several examples including Fokker-Planck equation in high dimensions, KuramotoSivashinsky equation, and vortex dynamics in fluids.

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CP30

Enforcing Conserved Quantities in Galerkin Truncation via Rons

Partial differential equations (PDEs) with conserved quantities pervade many areas of engineering, physics, and chemistry. Until recently, enforcing these conservation laws in reduced-order models has been challenging. The usual methodology has been to develop ad hoc methods for individual applications. However, with the recent development of Reduced-Order Nonlinear Solutions (RONS), we now have a unified framework for producing reduced-order models which preserve as many conserved quantities as needed. Here we present the application of RONS to usual Galerkin projections, but ensure that the conserved quantities are preserved in the reduced Galerkin model. We demonstrate the application of RONS on the one dimensional shallow water equation (SWE) as well as the two dimensional Navier-Stokes equations (NSE). For SWE we use a data driven reduced-order solution via proper orthogonal decomposition (POD). For NSE, we extend a common Fourier pseudospectral truncation to work in the RONS framework, ensuring that the truncated equations respect the conservation of Casimir invariants. In the case of SWE, we demonstrate that RONS circumvents the spurious finite-time blowup of the POD models. For NSE, we discuss the effects of Casimir invariants on the first and second order statistics.

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CP30

Quantum Pseudo-Integrable Hamiltonian Impact Systems

Quantization of a toy model of a pseudointegrable Hamiltonian impact system is introduced, including EBK quantization conditions, a verification of Weyl's law, the study of their wavefunctions and a study of their energy levels properties. It is demonstrated that the energy levels statistics are similar to those of pseudointegrable billiards. Yet, here, the density of wavefunctions which concentrate on projections of classical level sets to the configuration space does not disappear at large energies, suggesting that there is no equidistribution in the configuration space in the large energy limit; this is shown analytically for some limit symmetric cases and is demonstrated numerically for some nonsymmetric cases.

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CP31

New Results in Vortex Leapfrogging

We consider the leapfrogging vortex motion, discovered by Gröbli and by Love in the 1800s.This system describes the self-induced motion of of four in a two-dimensional inviscid fluid. The leapfrogging orbit consists of two rotating pairs of like-signed vortices which, taken as a quartet, propagate at con- stant velocity. It is known that if the two pairs are initially widely separated, the motion is stable, while if they are closer together it becomes unstable. We prove a longstanding conjecture that the bifurcation takes place when a certain parameter in the system equals 1/8. Time permitting, we will describe leapfrogging-like orbits in generalized systems of vortices.

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CP31

Exploring Regular and Turbulent Flow States in Active Fluids via Exact Coherent Structures

Exact coherent structures (ECSs) are spatiotemporally coherent stable or unstable exact solutions of the governing equations of a dynamical system that evolves in space and time. Examples include equilibria, periodic orbits, quasiperiodic orbits and traveling waves. It has been shown that ECSs, together with their invariant manifolds, serve as an organizing template of the complex dynamics of inertial fluid turbulence. We provide evidence that active matter systems, including confined active nematics that exhibit spontaneous flows, periodic defect dynamics, and chaotic 'active turbulence' can also be analyzed using the

ECS framework. This approach provides a deterministic picture of transition to active turbulence, and provides new tools for tackling the engineering problem of learning how to navigate the large space of spatiotemporal structures in active fluids. We also introduce ECSAct (Exact Coherent Structures in Active Matter), an open-source Python software that enables computation of ECSs and connecting orbits for active matter systems in confined geometries.

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CP31

Characterizing Data Assimilation in Navier-Stokes Turbulence with Transverse Lyapunov Exponents

Data assimilation of turbulent systems is crucial for many applications, including weather prediction, and related to the turbulence physics and mathematical properties of the Navier-Stokes equations. We propose a mathematical framework to study the assimilation phenomena characterized by the transversal stability of an invariant manifold containing a turbulent attractor, which we call a data-assimilation manifold. The transversal stability of the manifold is quantified by the transverse Lyapunov exponents. We conduct the Lyapunov analysis of the three-dimensional Navier-Stokes turbulence, which clarifies how the orbital instability of the turbulent attractor determines the occurrence of the data assimilation phenomena, particularly the critical length scale for the slaving small-scale dynamics.

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CP31

Phase Transitions in Two-Dimensional Foams with Wall Rupture

We construct Markov processes for modeling the rupture of edges in a two-dimensional foam. States of this process track network topologies through combinatorial embeddings. A mean-field rule is used to construct kinetic equations similar to the Smoluchowski coagulation equation with a multiplicative collision kernel. Multiple numerical simulations are run to confirm gelation behavior in the mean field model. We also look at some recent simple experiments involving squashed foams in glass panes as a basis of comparison.

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CP31

Data-Based Compact Models for Scalar Transport in Reoriented Flows

Scalar transport (e.g. heat, chemical species) in laminar flows is key to many industrial activities and stirring of the fluid by a forcing device (e.g. sliding walls or impellers) is an effective way to enhance this process. Such stirring typically involves switching between multiple forcing devices and in laminar flows thus accomplishes systematic reorientation of a base flow. Pro-active switching by model-predictive control (MPC) enables optimal process performance. Essential for practicable MPC is a model for the scalar evolution in the base flow that (i) is computationally fast and efficient and (ii) admits construction from standard CFD or experimental data. Such data-based modelling is demonstrated for the convective heating of a fluid via a hot boundary in a representative flow. The model relies on Dynamic-Mode Decomposition (DMD) of CFD temperature data and in its conventional form involves identifying the full set of dynamic modes from simulated temperature evolutions of all possible initial states. However, this is an intractable problem, since the number of initial states ("input space") and the spatial distribution of evolving states ("state space") have $O(10^5\text{-}10^6)$ degrees of freedom for standard CFD. The solution exists in data/model reduction by projection of the states on suitable bases. Compact models thus obtained (i) accurately predict the temperature for arbitrary switching protocols and (ii) are sufficiently fast and efficient for MPC.

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CP31

Drag Force on Spherical Particles Trapped at a Liquid Interface

The dynamics of particles attached to an interface separating two immiscible fluids are encountered in a wide variety of applications. Here we present a combined asymptotic and numerical investigation of the fluid motion past spherical particles attached to a deformable interface undergoing uniform creeping flows in the limit of small Capillary number and small deviation of the contact angle from 90 degrees. Under the assumption of a constant three-phase contact angle, we calculate the interfacial deformation around an isolated particle and a particle pair. Applying the Lorentz reciprocal theorem to the zeroth-order approximation corresponding to spherical particles at a flat interface and the first correction in Capillary number and correction contact angle allows us to obtain explicit analytical expressions for the hydrodynamic drag in terms of the zeroth-order approximations and the correction deformations. The drag coefficients are computed as a function of the three-phase contact angle, the viscosity ratio of the two fluids, the Bond number, and the separation distance between the particles. In addition, the capillary force acting on the particles due to the interfacial deformation is calculated.

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CP32

Topological Data Analysis of Myoblast Self-Assembly

Myoblasts are stem cells that eventually differentiate and fuse to become muscle fibers. Before mature tissues are formed, myoblasts must align themselves into coordinated structures that template the architecture of functional muscle tissues. The mechanisms driving this process are not yet fully understood. Current attempts to probe this behavior rely on user analysis of video and image data. Our work focuses on leveraging tools from topological data analysis to represent this system's evolving dynamics. We present an analysis of two videos of myoblast self-assembly and fusion. In one video, the cells are treated with blebbistatin, a motor-protein inhibitor. The other video serves as a control. Our research begins with an analysis of several methods of data preparation, such as different edge detection algorithms, to generate point clouds from both videos. We then perform topological analysis two ways: first by creating a Rips filtration of the point clouds and second via a cubical filtration of the original video frames. Finally, we generate CROCKER plots to represent the evolving topology of these myoblasts and present a comparative analysis of the results. Our work provides methods for comparing CROCKER plots, a finding which can be extended to other time series data. Additionally, our research provides insight into strategies for automating the analysis of stem cell self-assembly, providing valuable information about the mechanisms driving dynamic cellular behaviors.

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CP32

Topological Data Analysis of Spatiotemporal Honeybee Aggregation

A primary challenge in understanding collective behavior is characterizing the spatiotemporal dynamics of the group. We employ topological data analysis (TDA) to explore honeybee aggregations in the context of trophallaxis: the direct exchange of food among nestmates. Beginning with synthetic datasets from an agent-based model of trophallaxis, we build topological summaries called CROCKER plots to capture the shape of the data as a function of both scale and time. To detect important phase changes during the trophallaxis, we apply clustering and change-point detection methods to the norms of these CROCKER matrices. Our results show two distinct regimes corresponding to successive phases of the dynamics: a dispersed phase before the food is introduced, followed by a food-exchange phase in which clusters form. To further test our methods, we apply them to laboratory honeybee experiments. Our method successfully detects the same two phases across multiple food-exchange experiments and also reveals an additional change point towards the end of the experiments, suggesting the possibility of another dispersed phase following the food-exchange phase. Finally, using a combination of CROCKER plots and chi-squared analysis on experimental data, we enhance our mechanistic understanding of food-exchange behavior. The results from our TDA-based analysis are currently being used for validation and parameter inference to improve our in-house trophallaxis model.

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CP32

Compositional Analysis of Microbiome Data Reveals Time-Dependent Effects of Antibiotic Treatment

Microbiome studies typically account for compositionality using distance-based analysis, which results in restricted and low-power statistical analysis. Compositional Data Analysis (CODA)-approaches overcome this, but require lossy transformations of microbiome data that reside in a high-dimensional simplex to a tractable Euclidean subspace for multivariate analysis. Here, we introduce a CODA-based in-the-simplex approach for longitudinal microbiome data analysis in patients with chronic respiratory disease recruited as part of a placebo-controlled clinical trial evaluating the efficacy of treatment. Assessment of microbial perturbation as residuals in the simplex space reveals microbial changes due to treatment intervention undetectable by classical distance-based analysis. Ternary plots on moving differences of microbial compositions in the simplex indicate a time-dependent effect of treatments. The CODA-based 'in-the-simplex' approach for microbiome data opens up new avenues for further research and has the potential to inform future personalized interventions.

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CP32

Multiple Trajectories Method for Time Series Analysis

Statistical techniques (ARIMA, Holt-Winters, regressions) for time series data help smoothing noise/external effects for short-term forecasts. This does not necessarily assist in understanding of underlying processes. Instead of a single trajectory's approximation, we reconstruct dynamical systems. This allows treating external effects as switches between initial conditions. The dynamical systems' reconstruction accounts to physical principles and data fitting. Examples demonstrate accurate short-term prediction and approximation of global dynamics. Qualitative analysis of the latter shows various scenarios of process development.

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CP32

Optimization of Attractor Deformation Techniques

Valuable information about how system parameters are varying is encoded in changes to the shape and size of a nonlinear system attractor. Being able to analyze attractor deformation to infer system changes is important in many practical applications such as damage detection and structural health monitoring. Broadly speaking, two classes of methods have been proposed for analyzing attractor deformation: trajectory-based methods and geometry-based methods. Trajectory-based methods rely on time series prediction to estimate changes in the location or separation of trajectories at future points in time to determine parameter changes. Geometry-based methods rely on density or shape measurements of the overall system attractor to determine parameter changes. This work presents methods for optimizing the performance of both types of analysis, focusing on sensitivity vector fields (SVFs) and boundary transformation vectors (BTVs) as representatives of each class. In the case of SVFs, machine learning methods are used to determine the best time horizon, neighborhood size, and attractor locations for estimating system parameter changes. For BTVs, optimization methods are used to determine the Poincare sections most sensitive to changes in particular parameters. Both methods are used to infer system changes for several different system attractors, and the optimizations are demonstrated to significantly improve the ability to estimate small system parameter changes.

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CP32

Statistical Inference for Sparse Reconstruction and Fixed Point Analysis of Dynamical Systems

The reconstruction of nonlinear ordinary or partial differential equations from time series data has become an active area of research with applications in many scientific disciplines. A common statistical approach to this problem relies on sparse regression, whereby equations of the form dx/dt = f(x(t)) are estimated by regressing time derivatives on a large set of candidate functions, such as polynomials, with the intention of identifying a small subset of functions whose linear combination accurately captures the underlying dynamics of the system. Few methods exist for quantifying the uncertainty in the reconstructed equations, however, as well as for using these equations to identify and classify fixed points of the system. In this talk, we propose leveraging recent advances in Bayesian and frequentist sparse regression to estimate differential equations as sparse combinations of terms that are statistically signi?cant or have high posterior probabilities. Doing so provides greater robustness to noise than standard sparse regression techniques and allows for the uncertainty in individual terms and fixed points to be quantified. We discuss the application of fixed point methods to differential equations that are reconstructed in this way from time series and illustrate the methodology on noisy data generated from several dynamical systems.

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CP33

Using Scaling-Region Distributions to Select Embedding Parameters

Reconstructing state-space dynamics using time-delay embedding requires choosing values for the delay and the dimension. The embedding theorems do offer formal guidance for this; in practice, though, one has to resort to heuristics to make these choices. Best practice suggests an iterative approach: a heuristic is used to make a good first guess for the corresponding free parameter and then an asymptotic invariant approach is then used to firm up the value, e.g., computing the correlation dimension for a range of values around that initial guess and looking for convergence. This process can be subjective, as these computations often involve finding, and fitting a line to, a scaling region in a plot of the results of some calculation: a process that is generally done by eye and is not immune to confirmation bias. Moreover, few of these heuristics provide confidence intervals, making it difficult to say what convergence is. We propose an approach that automates the first step, removing the subjectivity, and formalizes the second, offering a statistical test for convergence. This approach rests upon a recently developed method for automated scaling-region selection that includes confidence intervals on the results. We demonstrate this methodology by selecting values for the embedding dimension for a number of data sets from real and simulated dynamical systems. We note that this method extends to any algorithmic free parameter in the delay-reconstruction procedure.

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Input-State Finite Time Stabilization of Sampled Data Control for T-S Fuzzy Large-Scale Dynamical System with Affine Matched Membership Function

This article aims to examine the problem of input-state finite time stabilization of sampled data control for T-S fuzzy large-scale systems with time delay and disturbances. The mode dependent non-linear systems are challenging to study in most general scenarios. The nonlinear system can be linearized by a fuzzy model with weighted membership functions to tackle this issue. To be more precise, new parallel distributed compensation (PDC) controller design is firstly proposed for fuzzy system, then affine transformed membership function is adopted by scaling and biasing the original membership function. To stabilize and to reduce the communication burden, sampled data feedback control is utilized for the considered system. By endowing Lyapunov stability theory, a set of sufficient conditions are developed in the frame of linear matrix inequalities to guarantee that the fuzzy system is input-state finite time stable. Finally, two numerical examples that are useful in the field of engineering are provided to demonstrate the effectiveness of the proposed method.

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CP33

Statistics of Attractor Embeddings in Reservoir Computing

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

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CP33

Energy Efficient Data Collection Using Mobile Sinks Based on Clipped Double Q-Learning Algorithm in Wireless Sensor Network

Mobile sinks (MS) are used in wireless sensor network (WSN) to address one main key issue called energy hole problem. Though MS has number of advantages such as increasing the security of the network, improving the network lifetime and packet drop rate, determining the best trajectory is an NP-hard problem. So, we have proposed a mobile sink movement based on clipped double Q-learning algorithm to reduce the energy hole issues. The proposed work selects an adaptive sojourn trajectory and position mainly based on the networks energy depletion. The results show the superiority of the proposed work in terms of energy consumption, network lifetime and packet delay.

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CP33

Symbolic Dynamics of a Driven Time-Delay System

The combination of time delay and periodic forcing has been studied in contexts such as climate systems, where it has been observed to produce a rich bifurcation structure of torus bifurcations and Arnold tongues. However, such systems generally cannot be solved analytically. Numerical solutions demonstrate the rich dynamics produced by this combination of features, but the mechanism by which these dynamics emerge remains unclear. To address this, we study an elementary piecewise-linear system with time delay and periodic forcing. By introducing a symbolic representation for the dynamics of the system, we derive analytic solutions. We further demonstrate clear mechanisms for how these solutions undergo border-collision bifurcations, allowing us to analytically map the bifurcation structure of the system.

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MS1

Adaptive Network Models in Heterogeneous Envi-

ronments

In human social systems, it is natural to assume that individuals' opinions influence and are influenced by their interactions. Mathematically, it is common to represent such systems as networks, where nodes are individuals and edges between them denote a connection. Adaptive network models explore the dynamic relationship between node properties and network topology. In the context of opinion dynamics, these models often take the form of adaptive voter models, where there are two mechanisms through which network changes can take place. Through homophily, an edge forms between two individuals who already agree. Through social learning, an individual adopts a neighbor's opinion. In these models, individuals are more frequently attached to those who share their opinion, seen through the formation of sub-communities of like-minded individuals. However, it is not always the case that individuals want to cluster into homogeneous groups. Instead, they might attempt to surround themselves with those who both agree and disagree with them to attain a balance of inclusion and distinctiveness in their social environments. In this work, we explore the effects that such heterogeneous preferences have on the dynamics of the adaptive voter model.

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MS1

Idea Engines: Connecting Innovation and Obsolescence from Markets and Genetic Evolution to Science

Innovation and obsolescence describe dynamics of ever-churning and adapting social and biological systems, concepts that encompass field-specific formulations. We formalize the connection with a toy model of the dynamics of the space of the possible (e.g. technologies, mutations, theories) to which agents (e.g. firms, organisms, scientists) couple as they grow, die, and replicate. We predict three regimes: the space is finite, ever growing, or a Schumpeterian dystopia in which obsolescence drives the system to collapse. We reveal a critical boundary at which the space of the possible fluctuates dramatically in size, displaying recurrent periods of minimal and of veritable diversity. When the space is finite, corresponding to physically realizable systems, we find surprising structure. This structure predicts a taxonomy for the density of agents near and away from the innovative frontier that we compare with distributions of firm productivity, covid diversity, and citation rates for scientific publications. Remarkably, our minimal model derived from first principles aligns with empirical examples, implying a follow-the-leader dynamic in firm cost efficiency and biological evolution, whereas scientific progress reflects consensus that waits on old ideas to go obsolete. Our theory introduces a fresh and empirically testable framework for unifying innovation and obsolescence across fields.

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MS1

Forecasting U.S. Elections Using a Compartmental Republican-Undecided-Democratic Model

Election dynamics are a rich complex system, and forecasting U.S. elections is a high-stakes problem with many sources of subjectivity and uncertainty. In this talk, we take a dynamical-systems perspective on election forecasting, with the goal of helping to shed light on the forecast process and raising questions for future work. By adapting a Susceptible-Infected-Susceptible model to account for interactions between voters in different states, we show how to combine a compartmental approach with polling data to produce forecasts of senatorial, gubernatorial, and presidential elections at the state level. Our results for the last two decades of U.S. elections are largely in agreement with those of popular analysts. We use our modeling framework to determine how weighting polling data by polling organization affects our forecasts, and we explore how our forecast accuracy changes in time in the months leading up to each election.

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MS1

Modeling the Spread of Clostridioides Difficile in Hospitals

Individual human behavior gives rise to emergent contact patterns, which are, in turn, a substrate upon which social and biological contagion can spread and evolve. This perspective has led to a beautiful and expansive modeling literature—a theoretical laboratory for understanding the fundamental principles underpinning contagion in social systems. However, it is much more challenging to reconcile the predictions of these theories to empirical observations because the data needed to fit contagion models are almost always lacking. In this talk, we argue that a highly controlled and measured environment—the hospital setting—is our best shot at validating the theories of contagion with empirical observations and implementing impactful interventions based on these theories. For the sake of concreteness, we introduce a contagion model for a specific pathogen, Clostridium Difficile, which is spread when healthcare workers and patients infect their environment, and vice versa. We develop a Bayesian framework to estimate the dynamical trajectory of this model with available electronic health records and highlight the data and modeling challenges that this approach involves.

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MS2

Operator Algebras for Data Assimilation and Forecasting of Dynamical Systems

Over the past three decades, Koopman and transfer operator techniques have proven to be highly fruitful in the analysis and forecasting of observables of dynamical systems. These methods are generally formulated in spaces of functions or measures with an abelian algebraic structure. In this talk, we discuss a family of techniques focusing on the induced action of Koopman and transfer operator on non-abelian algebras of operators. A common theme of these methods is structure-preserving finite-dimensional approximation. Specifically, we discuss positivity-preserving approximation of observables based on multiplication operators and approximation of the Koopman generator that preserve the Leibniz rule using inner derivations. We illustrate these methods with applications to data assimilation and subgrid-scale modeling (closure) of dynamical systems.

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MS2

Existence and Uniqueness of Koopman Eigenfunctions Near Stable Equilibria and Periodic Orbits

This talk will describe an existence and uniqueness theory for smooth Koopman eigenfunctions in the vicinity of an exponentially stable equilibrium or limit cycle. Uniqueness of finitely smooth principal eigenfunctions is implied by appropriate nonresonance and spectral spread conditions on the eigenvalues of the linearized dynamical system; existence is implied by the same and corresponding smoothness of the dynamics. Moreover, for infinitely smooth eigenfunctions and nonresonant dynamics a complete classification is obtained. The uniqueness and classification results are the first of their kind for non-analytic dynamics, and the existence result is significantly stronger than those from previous literature. Simple counterexamples demonstrate that the results are fairly tight.

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MS3

Nanoscale Patterns Produced by Ion Bombardment of Solid Surfaces

Bombarding a solid surface with a broad ion beam can produce a remarkable variety of nanoscale patterns. Oblique-incidence bombardment, for example, can lead to the formation of surface ripples with wavelengths as short as 10 nanometers. The anisotropic Kuramoto-Sivashinsky (AKS) equation has traditionally been used to model the formation of these ripples. The equation of motion for the surface can be rigorously derived for angles of ion incidence just above the threshold angle for ripple formation. In the case of two diametrically opposed, obliquely-incident ion beams, the equation of motion close to threshold and at long times is a simplified version of the AKS equation, and the ripples that form are disordered. In contrast, if the surface is bombarded with a single obliquely-incident beam, the behavior is dramatically different: highly ordered ripples can emerge at sufficiently long times. This order results from the combined effect of the nonlinearity and strong linear dispersion. Experiments show that nanoscale patterns can also form if a solid is bombarded with ions that have an energy too low to produce sputtering. If the solid is bombarded with two diametrically opposed, obliquely-incident beams of this kind, highly ordered, faceted ripples emerge for angles of incidence just above threshold. The equation of motion in this case is a generalized, anisotropic version of the Cahn-Hilliard equation.

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MS3

Ultrafast Laser-Induced Surface Complexity at the Nanoscale

Ultrafast laser pulses (100fs) spatio-temporally confine a large number of photons, enabling them to sculpt any solid surface achieving ultimate scales of structuring below 100nm. Upon multi-shot irradiation the self-organization and growth of periodic patterns arise from localized perturbations of the optical coupling on random surface nanoreliefs. Liquid flows are driven by laser-induced energy gradients and frozen by quenching. Transient patterns are then destabilized by successive light-surface coupling that reveal signatures of complexity. Some surface structures have optical/plasmonic periods while others show symmetry breaking characteristics of nonlinear fluid dynamics, interrogating on the underlying competition that drives the organization. One of the challenges is to develop a general model that inherit relevant symmetry and scale invariance properties and that contain the nonlinear dynamics able to reproduce dissipative structures in spatially extended systems. A Swift-Hohenberg modelling is proposed to reproduce hydrodynamic fluctuations at the onset of convective instability that we have recently demonstrated as the very nature of the laser-induced self-organized nanopatterns. I will show that the complexity of surface 2D patterns emergence can be finally learned by a deep convolutional network to connect the model coefficients to the experimental irradiation conditions, providing key laser process parameters to design a specific pattern.

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MS3

Fronts in the Wake of a Parameter Ramp: Slow Passage Through Folds and Pitchforks

The interaction of spatio-temporal heterogeneities with coherent structures, such as periodic patterns, fronts, and pulses, has relevance in a variety of applications, such as light sensing reaction-diffusion systems, crystal solidification, and fluid flows. In the context of the prototypical Allen-Cahn equation, we discuss the formation of front solutions in the presence of a stationary and moving parameter ramp which moderates the (in)stability of a spatially-homogeneous equilibrium and nucleates a traveling wave in its wake. In particular, we study a heterogeneity which is slowly varying in space. In the moving case, we find the front location is governed by the local transition between convective and absolute instability, and the slow-variation of the ramp causes a further delay of instability. In the stationary case we find the front interface is determined by a special solution of the Painléve-II equation. We use tools of geometric singular perturbation theory, such as normally hyperbolic invariant manifolds and blow-up coordinates, to rigorously establish front solutions in an open interval of quenching speeds and show, somewhat counterintuitively, that the front interface location is governed by the dynamics of a slow-passage through a fold bifurcation for some speeds, and through a pitchfork bifurcation for others. If time allows, we'll also discuss open problems in pattern forming fronts for such ramps.

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MS3

Spiral Chimeras in Oscillatory Media with Nonlocal Coupling

Systems that can be classified as oscillatory media consist of small oscillating elements that interact with each other via some form of coupling. Interest in these systems stems from their ability to generate beautiful structures, including target patterns and spiral waves. When coupling between oscillators occurs over long spatial scales the set of unstable wavenumbers that generate these patterns is no longer constrained to a narrow band. This leads to interesting new structures like spiral chimeras. In this talk we go over our efforts to understand the emergence of these patterns. To model these systems we use an abstract integro-differential equation. We then analyze this model using the method of multiple-scales to formally derive two different approximations for the phase dynamics of the pattern. One which is valid in the far field and resembles a viscous eikonal equation, and a second one which is valid near the core of the pattern and gives rise to phenomena that resembles phase turbulence.

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MS4

Reliable Learning of Deep Neural Operators Informed by Physics or Sparse Observations for Safe Extrapolation

Deep neural operators such as deep operator networks (DeepONets) can learn nonlinear operators that map between infinite-dimensional function spaces via deep neural networks. Pure data-driven neural operators and deep learning models, in general, are usually limited to the interpolation scenario, where the new input to be predicted is contained in the support of the training data. However, in the inference stage of real-world applications, the input may lie outside the support, i.e., extrapolation, which leads to large prediction errors and unavoidable failure of deep learning models. Here, we aim to address the challenge of extrapolation for deep neural operators. First, we systematically investigate the extrapolation behavior of DeepONets. We then quantify the extrapolation complexity via the 2-Wasserstein distance between two function spaces and propose a new behavior of bias-variance trade-off for extrapolation with respect to model capacity. Then we develop a complete workflow, including extrapolation determination and five reliable learning methods, to guarantee a safe prediction under extrapolation by requiring additional information—the governing PDEs of the system or sparse new observations. The proposed methods are based on either fine-tuning a pre-trained DeepONet or multifidelity learning. We demonstrate the effectiveness of the proposed framework over various types of parametric PDEs.

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MS4

Machine Learning Accelerated PDE Observers

State estimation is important for a variety of tasks, from forecasting to substituting for unmeasured states in feedback controllers. Performing real-time state estimation for PDEs using provably and rapidly converging observers, such as those based on PDE backstepping, is computationally expensive and in many cases prohibitive. We propose a framework for accelerating PDE observer computations using learning-based approaches that are much faster while maintaining accuracy. In particular, we employ the recently-developed Fourier Neural Operator (FNO) to learn the functional mapping from the initial observer state and boundary measurements to the state estimate. By employing backstepping observer gains for previously-designed observers with particular convergence rate guarantees, we provide numerical experiments that evaluate the increased computational efficiency gained with FNO. We test the ML-accelerated PDE observers in three benchmark examples: first, for a reaction-diffusion (parabolic) PDE whose state is estimated with exponential convergence; second, for a parabolic PDE with exact prescribed-time estimation; and, third, for a pair of coupled first-order hyperbolic PDEs that modeling traffic flow density and velocity. The ML-accelerated observers can achieve up to three orders of magnitude improvement in computational speed compared to classical methods. This demonstrates the attractiveness of the ML-accelerated observers for real-time state estimation and control.

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MS4

Operator Learning for Stochastic Closures of Complex Dynamical Systems

Closure models are widely used in simulating complex multiscale dynamical systems such as turbulence and Earths climate, for which direct numerical simulation that resolves all scales is often too expensive. For those systems without a clear scale separation, deterministic and local closure models often lack enough generalization capability, which limits their performance in many real-world applications. In this talk, we present a data-driven modeling framework for constructing stochastic and nonlocal closure models from (i) abundant data, and (ii) a limited amount of data. Specifically, operator learning with indirect data will be demonstrated in the context of stochastic differential equations. We also show how different types of regularization can be imposed to improve the performance of the learned closure models. The results show that the proposed methodology provides a systematic approach to constructing generalizable data-driven closure models, especially for multiscale dynamical systems without a clear separation between resolved and unresolved scales.

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MS4

On Learning the Dynamical Response of Nonlinear Control Systems with Deep Operator Networks

We propose a Deep Operator Network (DeepONet) framework to solve the time-dependent problems. Particularly, we want to learn the solutions of continuous-time nonlinear control systems from data. To this end, we first construct and train a DeepONet that approximates the control system's local solution operator. Then, we design a numerical scheme that recursively uses the trained DeepONet to simulate the control system's long/medium-term dynamic response for given control inputs and initial conditions. We accompany the proposed scheme with an estimate for the error bound of the associated cumulative error. Furthermore, we design a data-driven Runge-Kutta (RK) explicit scheme that uses the DeepONet forward pass and automatic differentiation to better approximate the system's response when the numerical scheme's step size is sufficiently small. Numerical experiments on the predator-prey, pendulum, and cart pole systems confirm that our DeepONet framework learns to approximate the dynamic response of nonlinear control systems effectively.

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MS5

Distinct Excitatory and Inhibitory Bump Wandering in a Stochastic Neural Field

Cortical recordings from non-human primates performing parametric working memory tasks reveal activity bumps that represent continuum variables over short periods devoid of stimulus, suggesting the underlying networks behave like continuum or metastable attractors. Such attractors emerge in neural field models with lateral inhibitory connectivity, in which response errors are well-characterized when including stochasticity. Both pyramidal(excitatory) neurons and interneurons(inhibitory) exhibit such directionally tuned bumps of activity, but such distinct bumps are often ignored in combined E/I Amari-type models. In past work, we analyzed stochastic bump dynamics in neural fields with separate excitatory/inhibitory populations, leveraging asymptotic to link bump motion to network architecture. Features of the inhibitory bump profile can indeed affect the stability and diffusion of the excitatory bump, ultimately shaping response error. We have also extended our models to include short-term presynaptic plasticity, which can facilitate or depress connections between neurons on a slower timescale in an activity-dependent way. We develop low-dimensional descriptions of this multiscale model to examine how short-term plasticity shapes the stability and stochastic dynamics of bumps.

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MS5

Complexities of the Cytoskeleton: Integration of Scales

Biological systems are traditionally studied as isolated processes (e.g. regulatory pathways, motor protein dynamics, transport of organelles, etc.). Although more recent approaches have been developed to study whole cell dynamics, integrating knowledge across biological levels remains largely unexplored. In experimental processes, we assume that the state of the system is unknown until we sample it. Many scales are necessary to quantify the dynamics of different processes. These may include a magnitude of measurements, multiple detection intensities, or variation in the magnitude of observations. The interconnection between scales, where events happening at one scale are directly influencing events occurring at other scales, can be accomplished using mathematical tools for integration to connect and predict complex biological outcomes. In this work we focus on building inference methods to study the complexity of the cytoskeleton from one scale to another.

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MS5

Identifying Landslides Using Multilayer Networks

There is concern that hillsides are likely to transition from slow creep to catastrophic failure due to heavy rainfall, which is predicted to increase because of climate change. While the pre-failure deformation is sometimes apparent in retrospect, it remains challenging to predict the sudden transition from gradual deformation to runaway acceleration. We use multilayer networks to investigate the spatiotemporal patterns of slow deformation at an active landslide: Mud Creek, a steep hillslope in the California Coastal Ranges that underwent catastrophic failure in 2017. Using a disordered mesh, we transform the study site into a spatially-embedded network in which the nodes are patches of ground and the edges that connect them are weighted with measurements of ground surface displacement and topographic slope to distinguish between fast moving and stable areas. This spatially-embedded network is represented as a multilayer network where each layer represents a snapshot of ground deformation taken by satellites. We use community detection, which identifies strongly-correlated clusters of nodes, to identify patterns of instability, and develop a metric, community persistence, to quantify patterns of ground deformation leading up to failure. This method is able to detect Mud Creek, as well as two other creeping landslides within the vicinity. We explore how this method performs on other creeping landslides, such as those found in the California Coastal Ranges.

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MS5

Parallel Reservoir Computing for Forecasting the Dynamics of Complex Networks

Several recent studies have demonstrated the utility of reservoir computing for forecasting the dynamics of complex systems in a variety of contexts. Reservoir computing is a specific kind of recurrent artificial neural network architecture that leverages the internal complex dynamics of the "reservoir" in order to forecast complex systems. In this work, we show that we can forecast the dynamics of not only individual time series or spatiotemporal systems, but of large complex networks. We achieve this by constructing a parallel RC architecture that mimics the topology of the network of interest. We achieve good predictions in cases where the network links are known and also in cases where the network links are unknown and inferred via a data-driven approach to approximately optimize prediction.

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MS6

Covering Relations, Cone Conditions and Horseshoe Blenders

We present a blender construction, which is based on correct topological alignment of sets combined with propagation of cones. It is applicable in arbitrary dimension and can be applied to obtain multidimensional blenders. The assumptions of our theorem allow for a rigorous, interval arithmetic based, computer assisted validation. We apply the method to the Hénon-like family of diffeomorphisms, obtaining a computer assisted proof of the existence of blenders for a given parameter range.

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MS6

Transition to Chaos in a System of Two Coupled Photonic Crystal Nanocavities

Photonic crystal (PhC) cavities have recently gained a lot of attention due to the possibility of doing nonlinear optics with small photon numbers, threshold-less lasing, and many other intriguing experiments at the interface of both classical and quantum optics. Two-coupled, driven, and lossy PhC nanocavities are of particular interest, as they are an experimental candidate of the open two-site Bose–Hubbard dimer model —a fundamental quantum mechanical model that accounts for the dynamics of bosons at two interacting sites—. Our work aims to characterize different observable dynamics in the semiclassical approximation of this quantum model —a four-dimensional autonomous vector field— to understand the PhC nanocavities' behavior. This talk will focus on different chaotic behaviors observed in the semiclassical approximations as the pump power f and the detuning of the driving signal δ are varied. By taking a geometrical approach, we translate the problem of identifying these different chaotic behaviors into a problem of finding intersections between stable and unstable manifolds in four-dimensional phase space. We then use state-of-the-art numerical techniques based on the continuation of suitable two-point boundary problems to find such intersections. This way, we create a theoretical and numerical framework that allows us to understand and delimit regions in the (f, δ)-plane where such behaviors are observed.

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MS6

Wild Lorenz Attractors in a Three-Dimensional Hnon Map and in Its Inverse

Lorenz attractors play an important role in the modern theory of dynamical systems. The reason is that they are robustly chaotic, i.e. they preserve their chaotic properties under various kinds of perturbations. This means that such attractors can exist in applied models and be observed in experiments. It is known that discrete Lorenz attractors can appear in local and global bifurcations of multidimensional diffeomorphisms. The first such result was established for a certain three-dimensional Henon map, – a quadratic map with a constant Jacobian. In this presentation, I discuss the possibility for the inverse map of this Henon map also to have discrete Lorenz attractors. The idea is to find a fixed or periodic point with eigenvalues (-1, -1, +1) and check the normal form coefficients. The main result is a numerically established existence of a period-six orbit with the required linear part. Then the sixth iteration of the map can be approximated by a flow that is equivalent to the Shimizu-Morioka system. This means that the map and its inverse both can possess discrete Lorenz attractors

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MS6

Transitions to Wild Chaos in a Four-Dimensional Lorenz-Like System

Wild chaos is the name given to a higher-dimensional form of chaotic dynamics that can only arise in vector fields of dimension at least four. Recently, Gonchenko, Kazakov and Turaev (2021) showed that a four-dimensional Lorenz-like vector field with an additional parameter has a wild chaotic attractor. This means that every orbit in the attractor is unstable and that specific conditions hold and guarantee the persistence of this instability property. We investigate in a two-parameter setting how this wild chaotic attractor arises geometrically. As a starting point, we continue the bifurcation structure of the equivalent three-dimensional classic Lorenz equations when this additional parameter is "switched on". In particular, we find that the homoclinic explosion point of the classic Lorenz equations unfolds and gives rise to different types of global connections of the four-dimensional system. Due to the new feature of spiralling near the origin, these connections are of Shilnikov type, and we also find fold, period-doubling and torus bifurcations of limit cycles. The overall bifurcation diagram provides new insight into the organisation of the four-dimensional phase space.

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MS7

Theory of Cellular Computations with Metastable States

Cells that operate in dynamic environments such as that of a developing organism or an adult tissue, continuously sense and respond to chemical signals that vary in space and time. In order to accurately interpret this complex information, the biochemical networks in single cells not only actively process the extracellular signals in real-time, but also, the principles underlying the biochemical computations must enable two seemingly opposed features: specificity in the input-response relationship must be ensured, whereas at the same time, the biochemical networks must enable generalization of the signal information, as it has been demonstrated that different chemical inputs can induce the same phenotypic output. We propose an alternative framework of describing single-cell biochemical computations as computations with transients. We consider the problem of biochemical networks subjected to external dynamic signal as an explicitly time-dependent dynamical system. The phenotypic response is thereby determined by the trajectory that describes the change of the state of the system, where a specific signal class maps to a unique class of dynamic trajectories that is a solution of the non-autonomous system. We identify a minimal dynamical principle that enables both specificity and generalization in the signal processing to emerge, and evaluate our hypothesis using computational models and single-cell protein activity data.

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MS7

Routes to Metastable Dynamics in Cortex and Implications for Cognitive Function

Neural activity in cortex is characterized by a rich repertoire of dynamical behaviors. Evidence is growing that these dynamics often resemble a sequence of discrete metastable states reminiscent of a Hidden Markov Model (e.g., in gustatory and prefrontal cortex). In other cases, neural dynamics may evolve along continuous trajectories that exhibit a strong dependence on initial conditions, reminiscent of chaotic dynamics. Yet another possibility is that neural dynamics evolve as in a glassy system, going through an exceedingly large number of fixed points, causing a considerable slowing down of the dynamics and taking over several hundreds time constants to 'forget' a perturbation. In a simulation of limited time duration, all these dynamics appear to be metastable, and it may be hard to infer the true underlying dynamics. In this talk, I will discuss recent theoretical models of different routes to neural metastable dynamics, the evidence (if any) from datasets of simultaneously recorded neurons, and the potential implications for cognitive processes such as expectation, memory and decision making.

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MS7

Connecting the Structure of Individual Networks to Nonlinear and Transient Dynamics in Oscillator Systems

New developments in network reconstruction are rapidly increasing the ability to map connection patterns in neural systems, ranging from the microscopic synaptic connection patterns between individual neurons to the macroscopic connectivity patterns between cortical areas. At the same time, however, a challenge commonly arises: even if we knew the complete connectivity diagram for a single model organism, how could we understand anything about the resulting nonlinear dynamics? Here, we present a novel framework to go from the connectivity of an individual network to the spatiotemporal pattern of oscillations in a network system. This approach allows us to analytically study the collective and transient behaviors of oscillator networks and offers a new, geometric perspective of synchronization phenomena in terms of the spectrum of the networks adjacency matrix. We then use this novel approach to study two important dynamical phenomena in network systems: (1) the emergence of synchronous oscillations and complex spatiotemporal patterns like chimera states, and (2) patterns of neural activity important for short-term memory that is dynamic, flexible, and modifiable online. These results provide new analytical insight into how sophisticated spatiotemporal dynamics arise from specific connection patterns in neural systems.

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MS7

Towards a Unifying Framework for Metastable Brain Dynamics

The brain, and neuronal circuits within, are commonly proposed to have metastable dynamics - typically thought of as a regime with a succession of long-lived states - as evidence from a wide variety of experiments has accumulated to suggest important cognitive and sensory roles for this behavior. However, a careful comparison between works in the literature reveals that the definition ascribed to metastability can vary widely and even be incompatible - for instance, some consider noise to be essential for it, while others rule noise out. We attempt to solve these inconsistencies by discussing the observations and definitions of metastability in neuroscience and then using insights from dynamical systems theory to suggest a unifying definition for it. We use this definition as an umbrella term that encompasses most other definitions in the literature as distinct subtypes, for which we then discuss the possible dynamical mechanisms, properties, and functional roles. We believe this is a crucial step toward the development of a general framework for metastability in the brain.

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MS8

Topology of Phase Defects in Cardiac Excitation Patterns

Techniques from mathematical physics and modeling approaches have been used to gain a better understand and improve the treatment of the largest cause of death worldwide i.e. cardiac arrhythmias. Rotating electrical waves in the heart, called vortices or rotors, are widely accepted as the driving force for this pathology and therefore are the focus of our research. It was shown recently that at the core of cardiac rotors, there is an extended phase defect, comparable with branch cuts in complex analysis or domain walls in magnetism[doi: 10.1016/j.compbiomed.2021.104217, doi: 10.3389/fphys.2021.690453]. These phase defect lines were also found in experimental recordings of rabbit hearts[doi: 10.3389/fphys.2021.690453] and cardiac monolayers[doi: 10.1371/journal.pone.0271351]. In this talk, we present the building blocks of the vortices in terms of phase defects and the topological rules they must follow. For example, we can associate various types of topological charge with a phase defect. We relate this set of rules to the limited configurations of D-branes in string theory. We also apply our topological framework to simulations and experimental data by detecting the different topological structures and analyzing the emerging patterns. Together, our approach offers a new language for both the analysis and a more fundamental description of heart rhythm disorders.

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MS8

Dynamical Issues Arising During 3D Cardiac De-

fibrillation

We have been developing a new, 3D low-energy defibrillation method, which works by modifying the filaments around which scroll waves rotate into configurations that tend to shrink and disappear. This process sometimes fails, when the filaments reconfigure themselves into unfavorable shapes, a process we call "flopping." In this talk, we will describe the dynamics of flopping, and discuss possible methods for its avoidance.

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MS8

Experimental Quantification of Chaos in Cardiac Tissue; Lyapunov Exponents and Period-Three Orbits

Many models of cardiac cells exhibit chaotic dynamics implying a nonlinear approach to stabilize irregular heart rhythms of cardiac disease. However, little experimental evidence has been collected to justify this description. This study aims to both quantify and qualify the chaotic nature of cardiac tissue from the systems arrhythmic electrical response to a range of fast periodic stimuli. Leading Lyapunov Exponents were calculated from time series of single cell frog action potential durations (APDs) yielding negative exponents for forcing frequencies near APD bifurcation events and positive exponents for arrhythmic response. Additionally, several examples of stable period-three orbits and unstable periodic orbits of action potentials were found during single cell arrhythmic responses to periodic pacing. Similar transient coherent structures were identified for multicellular optical mapping measurements of voltage activity during ventricle fibrillation of pigs and even humans. These observations further illustrate that cardiac tissue response is not stochastic but rather chaotic suggesting methods to control and terminate arrhythmias.

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MS8

Experimental Observation of Alternans-Induced Phase-2 Reentry in Brugada Syndrome by Optical Mapping on an Explanted Human Heart, with Numerical Simulation Validation

Brugada syndrome is known to be a genetic heart disease that can lead to ventricular fibrillation (VF). It has been postulated that VF is produced by a phase-2 reentry resulting from areas with mismatched action potential duration (APD). While this has been shown numerically and in some experiments with MAP recordings, to date there is no full detailed experimental observation of the phase-2 induction. We use high-resolution optical mapping in an explanted human heart to quantify the induction of VF by phase-2 reentry in a Brugada-induced model. A rejected-for-transplant human heart was arterially perfused and the endocardial right ventricle was optically mapped with a voltage-sensitive dye and the electrical propagation was measured at high spatial and temporal resolution (256x256 pixels, at 500 Hz) over a large field of view (40 cm2). When paced at 900ms, there was induction of pronounced APD alternans that developed into spatially discordant alternans, which led to areas of long APD (tissue still depolarized) next to areas with very short APD (repolarized tissue), creating a mismatch in APD. This created a spatial voltage gradient that led to phase-2 reentry, generating an asymmetric figure-of-eight reentry that evolved into multiple spiral waves and VF. An ionic model for human ventricular cardiac cells was modified to fit the experimental voltage traces and was used to investigate the mechanism that reproduced the same experimental dynamics of phase-2 reentry.

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MS9

Cancer Metastasis as a Branching Process with Settlement

The mathematical modelling of metastasis is a challenge. The occurrence of metastasis is basically random, and the role of the host tissue is not at all clear. Based on biological observations of metastasis, I will introduce a stochastic branching process with settlement. Analysis of this stochastic process leads to interesting mean field equations in the form of birth-jump models. Stability conditions lead to the identification of a new metastasis classifier: the metastatic reproduction number. (Joint work with A. Rhodes and C. Frei).

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MS9

Estimation of Antibody Binding Kinetics via Parametrization of Spatially-Distributed Stochastic Particle Models

Surface Plasmon Resonance (SPR) assays are a standard approach for quantifying kinetic parameters in antibody-antigen binding reactions. Classical SPR approaches ignore the bivalent structure of antibodies, and use simplified ODE models to estimate effective reaction rates for such interactions. In this work we develop a new SPR protocol, coupling a model that explicitly accounts for the bivalent nature of such interactions and the limited spatial distance over which such interactions can occur, to a SPR assay that provides more features in the generated data. Our approach allows the estimation of bivalent binding kinetics and the spatial extent over which antibodies and antigens can interact, while also providing substantially more robust fits to experimental data compared to classical ODE models. I will present our new modeling and parameter estimation approach, and demonstrate how it is being used to study interactions between antibodies and spike protein. I will also explain how we make the overall parameter estimation problem computationally feasible via the construction of a surrogate approximation to the (computationally-expensive) particle model. The latter enables fitting of model parameters via standard optimization approaches.

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MS9

Short Time Diffusive Fluxes Over Membrane Receptors Yields the Direction of Signaling Sources

An essential ability of many cell types is to detect stimuli in the form of shallow chemical gradients. Such cues may indicate the direction the new growth should occur, or the location of a mate. Amplification of these faint signals is due to intra cellular mechanisms while the cue itself is generated by the noisy arrival of signaling molecules to surface bound membrane receptors. We present a new hybrid numerical-asymptotic technique coupling matched asymptotic analysis and numerical inverse Laplace transform to rapidly and accurately solve the parabolic exterior problem describing the dynamic diffusive fluxes to receptors. We observe that equilibration occurs on long timescales, potentially limiting the usefulness of steady state quantities for localization at practical biological timescales. We demonstrate that directional information is encoded primarily in early arrivals to the receptors, while equilibrium quantities inform on source distance. In the extreme scenario adopting the direction of the first impact to the cell, we find a surprisingly accurate directional estimate.

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MS9

Optimal Patterns of Traps that Minimize the Mean First Passage Time in Elliptical-Shaped Domains

The determination of the mean first passage time (MFPT) for a Brownian particle in a bounded 2-D domain containing small absorbing traps is a fundamental problem with biophysical applications. The average MFPT is the expected capture time assuming a uniform distribution of starting points for the random walk. We develop a hybrid asymptotic-numerical approach to predict optimal configurations of m small stationary circular absorbing traps. From the derivation of a new explicit formula for the Neumann Green's function and its regular part for the ellipse, a numerical approach based on our asymptotic theory is used to investigate how the spatial distribution of the optimal trap locations changes as the aspect ratio of an ellipse of fixed area is varied. The results from the hybrid theory for the ellipse are compared with full PDE numerical results computed from the closest point method For long and thin ellipses, it is shown that the optimal trap pattern for $m \leq 5$ identical traps is collinear along the semi-major axis of the ellipse. For such essentially 1-D patterns, a thin-domain asymptotic analysis is formulated and implemented to accurately predict the optimal locations of collinear trap patterns and the corresponding optimal average MFPT. Joint work with: Colin MacDonald (UBC), Sarafa Iyaniwura (Los Alamos) and Tony Wong (Brown University).

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MS10

A Model for the Intrinsic Limit of Cancer Therapy: Duality of Treatment-Induced Cell Death and Treatment-Induced Stemness

Intratumor cellular heterogeneity and non-genetic cell plasticity in tumors pose a recently recognized challenge to cancer treatment. Because of the dispersion of initial cell states within a clonal tumor cell population, a given therapeutic agent only kills a fraction of the cancer cells. Due to dynamic instability of cellular states, the surviving cells are pushed into a variety of functional states, including a stem-like state that confers resistance to treatment and regenerative capacity. This immanent stress-induced stemness competes against cell death in response to the same treatment and may explain the near-inevitable recurrence in certain cancers. This double-edged-sword mechanism of treatment complements the selection of preexisting resistant cells in explaining post-treatment progression. Here, we present a generic elementary model and analytical examination of this intrinsic limitation to therapy. We show how the relative proclivity of cells towards cell death versus transition into a stem-like state establishes either a window of opportunity for containing tumors or the inevitability of progression following therapy. The model considers measurable cell behaviors independent of specific molecular pathways and provides a new theoretical framework for optimizing therapy dosing and scheduling as cancer treatment paradigms move towards approaches that contain the tumor and avoid therapy-induced progression.

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MS10

Rethinking the Immunotherapy Numbers Game

Immunotherapies have improved response rates in a range of cancers, albeit for a subset of patients. This differential response may arise from the pre-treatment composition of, or complex interactions within, the tumor immune microenvironment. We use a mathematical model of cancer and the immune system to understand the impact of therapy on a patients tumor and local immune microenvironment, and how cytotoxic - immunotherapy combinations may used to improve patient outcomes.

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MS10

Enhancing Immunotherapies Using Combination Therapies: the Mathematics of Timing and Delivery

Ten years ago, Cancer Immunotherapy was heralded as the Breakthrough of the Year by Science magazine. In the intervening years, many immunotherapy treatments have been developed and put through clinical trials with limited success. One challenge is that the tumor microenvironment is immunosuppressive: the tumor cells produce molecules that block the anti-tumor activity of immune cells. Thus, we need to fight this immunosuppression by using combination therapies. For example, the tumor may produce molecules that block the anti-tumor activity of T-cells by binding to the Programmed Cell Death ligand. Therapies have been developed to block these molecules, but the question remains: how can we get the components of these combined therapies to the right place, at the right time, and in the correct amounts? In this talk, I will describe several mathematical models that attack this problem. These involve optimizing the timing of PD1-inhibitors, as well as modeling slow-release targeted delivery of multiple drugs in nano-particles.

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MS10

Quantifying Neoantigen Evolution and Response to Immunotherapy in Colorectal Cancer

Each cancerous colorectal tumor contains tumor-specific antigens (neoantigens). Because these neoantigens are present only in the tumor and not in healthy tissue, they are excellent targets for cancer immunotherapies. Checkpoint-blockade immunotherapy enables the patients native immune system to recognize tumor cells that were previously invisible due to immune escape, but this therapy has extremely heterogeneous patient outcomes, ranging from total failure to complete remission. We seek to understand how the mutagenic landscape of the tumor is related to therapeutic outcomes. First, we model neoantigen evolution using a stochastic branching-process model. Next, we use a dynamical model of anti-PD1 checkpoint-blockade therapy to predict response to therapy in these in-silico tumors. We relate therapeutic outcomes to heterogeneity of tumor mutational landscape, quantified by both the number of mutations in the tumor as well as the clonality of the neoantigens present in the tumor. We find that mutational burden, the total number of neoantigenic mutations present in the tumor, is insufficient to determine therapeutic outcome. Neoantigenic clonality, the fraction of tumor cells that contain a particular neoantigen, is key in determining response to therapy.

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MS11

SIS Epidemics on Graphons and Large Random Networks

Classical compartmental models of epidemics have only few variables, which correspond to the number of individuals in each compartment, and the ordinary differential equations that describe their evolution in time are obtained from assuming homogeneous interactions among all individuals. However, heterogeneity of interactions plays a crucial role in actual spread of diseases. In order to take into account the heterogeneity of the population, one can first consider a finite number of homogeneous sub-populations and a weighted graph describing their interactions. Since the study of larger and larger graphs becomes analytically or computationally intractable, this work aims at developing, analyzing, and validating suitable infinite-dimensional models. Our main finding is that SIS epidemics on large random networks can be well approximated by an infinite-dimensional integro-differential equation. Starting from a stochastic individual based description of an SIS epidemic spreading on a random network, we study the dynamics when the size of the network tends to infinity. In the limit, we recover an epidemic propagating on a graphon. Our results cover the case of dense and sparse graphs, when the number of edges is of order n^a with $a > 1$, but not the case of very sparse graphs with $a = 1$. The argument to establish our limit theorem exploits a coupling between the process of interest and an epidemic spreading on the complete graph but with a modified infectivity.

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MS11

On the Features That Matter (and Those That do Not)

I will present and discuss a data-driven approach to characterize nonidentifiability of a models parameters (and illustrate it through dynamic as well as steady kinetic models). By employing Diffusion Maps and their extensions, we will discover the minimal combinations of parameters required to characterize the output behavior of a chemical system: a set of effective parameters for the model. Furthermore, we introduce and use a Conformal Autoencoder Neural Network technique, as well as a kernel-based Jointly Smooth Function technique, to disentangle the redundant parameter combinations that do not affect the output behavior from the ones that do. I will also discuss the interpretability of our data-driven effective parameters, and demonstrate the utility of the approach both for behavior prediction and parameter estimation. In the latter task, it becomes important to describe level sets in parameter space that are consistent with a particular output behavior.

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MS11

Continuification-Based Control of Large-Scale Multiagent Systems in a Ring

A pressing open challenge in dynamical systems and control theory is to find methods to steer the collective behavior of large-scale multiagent systems consisting of many dynamical units (or agents) interacting with a given, and possibly time-varying, network topology. Examples of this problem include multirobot systems, cell populations, and human networks. Typically, in these applications, the goal is to control some macroscopic observables of the emerging collective behavior. However, control needs to be practically exerted at the microscopic, individual agent-level. Developing methods that translate macroscopic-level control goals into microscopic-level control actions is a critical challenge, about closing a feedback loop across different scales of descriptions. We propose a method to control large-scale multiagent systems. Specifically, we use a continuification-based approach that transforms the microscopic, agent-level description of the system dynamics into a macroscopic, continuum-level representation, which we employ to synthesize a control action towards a desired distribution of the agents. The macroscopic description of the closed-loop system is used to prove convergence and stability. Then, the continuum-level control action is discretized at the agent-level to practically implement it. The method is illustrated on the problem of controlling a swarm of mobile agents moving in a ring.

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MS11

Large Scale Traffic Monitoring and Control

We describe the I-24 MOTION open-road testbed led by the Tennessee Department of Transportation on Interstate 24 near Nashville, TN. The purpose of the testbed is to provide an experimental facility for testing traffic management, control, and the impact of automated vehicle technologies in real freeway traffic. The testbed consists of 300 pole-mounted 4K resolution video cameras providing uninterrupted coverage of 4 miles of the roadway. Video data is processed in real time into vehicle trajectories for all vehicles passing through the 8 lanes on the testbed location. The length of the testbed is currently of 4 miles (October 2022), with plans to expand to 6 miles. The data provided by the testbed represent an unprecedented amount of anonymized vehicle trajectories (4 order of magnitude higher than currently publicly available dataset), which can be used to unlock new traffic science, safety improvements, and driver modeling. In November 2022, the CIRCLES consortium will run a large-scale experiment taking advantage of this testbed. This is the first connected and automated vehicle experiment to be run on I-24 MOTION: 100 vehicles will be deployed to the highway with enhanced cruise control algorithms. Such algorithms are specially designed for dampening phantom traffic waves and improving the stability and energy consumption of the traffic stream.

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MS12

Dynamic Regime Change Detection Through the Inflated Dynamic Laplacian

Almost all Lagrangian analysis techniques rely on a specified flow time over which the Lagrangian analysis is carried out. Implicit in this flow time specification is that a "correct' or 'natural' flow time is known, that this flow time is a natural one for the entire domain, and that the system does not undergo regime changes in the underlying dynamics over this flow time. In practical situations, all of these conditions are rarely met. To address these issues in the context of emergent coherent dynamics, we introduce an inflated dynamic Laplace operator – built on the successful dynamic Laplacian technology – and the notion of semi-material coherent sets. Eigenfunctions of this inflated dynamic Laplacian identify the emergence and destruction of coherent objects – both the timing and the location in phase space. After introducing the dynamic Laplacian we will briefly discuss natural timescales in the single regime setting. We then describe the extension to the inflated dynamic Laplacian and illustrate this new multi-regime analysis technique on several examples, including from geophysics.

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MS12

Detecting Communities in Time-Evolving Networks

Community detection in time-evolving networks is a long-standing problem in network theory. In particular, the graph supra-Laplacian of the corresponding multiplex network has been used to characterise clusters or communities. In this work we port the inflated dynamic Laplacian constructed by Froyland and Koltai to graphs, which was used recently in the continuous domain to discover the birth and death of coherent sets. We look at the eigenproblem of the graph inflated dynamic Laplacian and present results on community detection and discovering balanced graph-cuts, motivated by classical isoperimetric problems.

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MS12

Detecting the Birth and Death of Finite-Time Coherent Sets

The decomposition of the state space of a dynamical system into almost invariant sets is important for understanding its essential macroscopic behavior. The concept is reasonably well understood for autonomous dynamical systems, and recently a generalization appeared for non-autonomous systems: coherent sets. Methods for identifying coherent sets, and Lagrangian coherent structures more generally, rely on coherence being present throughout a specified time interval. However, real coherent structures are ephemeral, continually appearing and disappearing. We present a new construction, based on a time-inflated dynamic Laplacian, that relaxes this materiality requirement in a natural way, and provides the means to resolve the births, lifetimes, and deaths of coherent structures.

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MS12

Network-Based Analysis of Lagrangian Transport and Mixing

Transport and mixing processes in fluid flows are crucially influenced by coherent structures and the characterisation of these Lagrangian objects is a topic of intense current research. Recently, computational approaches have been proposed to identify coherent sets directly from an ensemble of trajectories by means of a Lagrangian flow network, where the links are weighted according to spatio-temporal distances between tracer trajectories. In this talk, we discuss some extensions to the network-based framework. First, we consider the long-term behavior of coherent flow features by an adaption of evolutionary spectral clustering methods. Second, we demonstrate how to study and quantify advective and diffusive mixing within the network approach. We apply the proposed methods to several example systems, including turbulent Rayleigh-Bénard convection.

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MS13

Functional Dynamics and Coexistence of Cortical Wave Patterns

Self-organized patterns in the actin cytoskeleton are essential for eukaryotic cellular life. They are the building blocks of many functional structures that often operate simultaneously to facilitate, for example, nutrient uptake and movement of cells. Here, we present experimental results demonstrating that ring-shaped actin waves, commonly acting as precursors of macropinocytic cups, can mediate switches between different modes of motility, and may even trigger spontaneous, cell cycle-independent cytofission events in multinucleate, oversized amoeboid cells. However, identifying how qualitatively distinct actin patterns can coexist remains a challenge. Using bifurcation theory of a mass conserved activator-inhibitor system, we uncover a generic mechanism of how different actin waves traveling waves and excitable pulses organize and simultaneously emerge. Our experiments show that, indeed, narrow, planar, and fast-moving excitable pulses may emerge in a cell-size dependent manner and can coexist with the ring-shaped macropinocytic waves.

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MS13

Nuclei Serve as Pacemakers to Coordinate the Cell Cycle in Space and Time

Upon fertilization, the early *Xenopus laevis* frog egg quickly divides about ten times to go from a single cell with a diameter of a millimeter to several thousands of cells of somatic cell size. Using cytoplasmic extracts made from frog eggs, many cellular processes have been reconstituted and studied in vitro. Homogenized extracts can also spontaneously self-organize into various cellular spatial structures when mixing isolated components back together. Here, we will discuss our recent experimental and modeling efforts to understand how biochemical oscillations and waves form in the frog cytoplasm, and how they help organize the cell division cycle. We study an artificial cell system consisting of droplets of frog egg extracts of varying sizes, which allows characterizing the spatiotemporal dynamics of cell cycle oscillations, periodic nuclear assembly and destruction, and cytoskeletal organization. We complement our experimental analysis by developing computational models incorporating nuclear dynamics, illustrating the role of the nucleus in setting the cell cycle oscillation period. Nuclei are shown to function as pacemakers, regions which oscillate faster than its surroundings. As a result, nuclei send out biochemical waves that can synchronize the whole medium and ensure that cell division is properly coordinated in the large frog egg.

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MS13

Self-Organized Patterns in Amoeboid Aggregation

Upon starvation, Dictyostelium discoideum cells start secreting the chemoattractant cAMP. This chemoattractant is relayed by neighboring cells and the ensuing motion results in the formation of cell aggregates. Most commonly, experiments are performed using dense, confluent cell layers, which leads to streams of cells and large aggregates containing thousands of cells. We carried out experiments using lower cell density and observed the formation of small scale aggregates, consisting of several hundreds of cells. These small aggregates then underwent a coalescence process, which eventually resulted in much larger aggregates. We quantified this coalescence process and compared it to the motility-induced phase separation observed in self-propelled particle systems. Furthermore, we addressed the aggregation process using simulations.

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MS13

3D Tissue Dynamics in Dictyostelium

During culmination of Dictyostelium discoideum, cells undergo coordinated cellular movement and rearrangement to shape the final fruiting body anatomy. Cells reposition themselves from their original linear ordering along the antero-posterior axis to more convoluted three-dimensional layout with diploblastic-like radial symmetry. Time-lapse microscopic analysis of this dynamics is challenging due to the elongated tissue morphology encompassing large distances relative to the high speed of cell migration, thus we know surprisingly little about the dynamics - when and where cells move and in what way. Here we present our recent data obtained by light-sheet and confocal microscopy approach tailored to capture the hidden layers of this complex dynamics. We show that the initial stage of culmination is characterized by the appearance of a small cluster of ecmB expressing (PstB) cells at the tip region followed by polarization of rearrangement of neighboring cells. Our results hint at evolutionary convergence of spatio-temporal dynamics in metazoa and amoebozoa that serve critical roles in shaping multicellular tissues. We will discuss how some of the observed dynamics can be modeled and understood from an active material perspective and also based on an agent-based framework.

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MS14

Verifying Global Stability of Fluid Flows Using Sum-of-Squares Optimization

Verifying nonlinear stability of simple fluid flows against all perturbations is a classic challenge in fluid dynamics.

All past results rely on monotonic decrease of perturbation energy or of a similar quadratic integral. This "energy method" cannot show global stability of any flow in which perturbation energy may grow transiently. For the many flows that allow transient energy growth but seem to be globally stable (e.g. pipe flow and other parallel shear flows at certain Reynolds numbers) there has been no way to mathematically verify global stability. After explaining why the energy method was the only way to verify global stability of fluid flows for over 100 years, I will describe a different approach that is broadly applicable but more technical. This approach uses sum-of-squares polynomials to computationally construct non-quadratic Lyapunov functions that decrease monotonically for all flow perturbations. I will present a computational implementation of this approach for the example of 2D plane Couette flow, where we have verified global stability at Reynolds numbers above the energy stability threshold. This energy stability result for 2D Couette flow had not been improved upon since being found by Orr in 1907. The results I will present are the first verification of global stability, for any fluid flow, that surpasses the energy method.

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MS14

Analysis and Control of Time-Delay Systems Using Polynomial Optimization

The evolution of time delay systems (delay differential equations) depends on present and past values of the state. This dependence on state histories can lead to instabilities, bifurcations, and nonintuitive behaviors which are not found in analogous ODE systems. Some instances of time delay systems with their associated delays include epidemic models (incubation period), population dynamics (gestation time), and fluid modeling (transport time of fluid moving in a pipe). This work provides an overview of how polynomial optimization methods can be used to perform analysis and control of time-delay systems. Some of these applications include certifying stability, safety verification, and optimal control. The dualization of these programs leads to the definition of measure-valued solutions to time-delay systems.

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MS14

Converse Lyapunov Functions and How to Find Them

In this talk, we review recent advances in converse Lyapunov theory and its application to the use of Sum-of-Squares (SOS) optimization for analysis and control of nonlinear systems - a topic which includes: Domains of attraction, maximal invariant sets, minimal attractor sets, forward/backward reachable sets and optimal control. In each case, we review the applicable converse Lyapunov functions and show how these can be used to refine and accelerate the search for a corresponding Lyapunov-function-based proof via polynomial optimization methods such as SOS. We begin the talk with a general definition of what constitutes a converse Lyapunov function. We then review computational methods for finite-dimensional parameterization of Lyapunov functions LMIs, SOS, and the Positivstellensatz. We then consider converse Lyapunov results for exponential stability and decay rate, focusing on the question of existence of polynomial Lyapunov functions with degree bounds. Next, we consider two converse Lyapunov results for finding the maximal region of attraction and show how these functions can be found using SOS. We then turn to the problem of minimal attractive sets again characterizing these sets using converse Lyapunov functions and showing how to find these function using SOS. In the final part of the talk, we turn to optimal control. First, we formulate a general characterization of converse Lyapunov theory for this problem and show how the HJB equation and dynamic programming are special cases of this theory. We then show that the search for converse value functions may again be cast as an SOS problem. These results are then applied to the problem of estimating forward and backward reachable sets.

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MS15

Using Disorder to Overcome Disorder: a Mechanism for Frequency and Phase Synchronization in Complex Nonlinear Systems

Adding spatial heterogeneity to otherwise spatially homogeneous system may result in promoting synchronization and elimination of chaos [Y. Braiman, J. F. Lindner, and W. L. Ditto, Nature 378, 465 (1995); Y. Braiman, W. L. Ditto, K. Wiesenfeld, and M. L. Spano, Phys. Lett. A 206, 54 (1995); Y. Sugitani, Y. Zhang, and A. E. Motter, Phys. Rev. Lett. 126, 164101 (2021)]. Mechanisms responsible for such a phenomenon may vary and depend on coupling structure and system parameters. Recently, we have reported a new type of disorder-enhancing mechanism, observed in a model that describes the dynamics of external cavity-coupled semiconductor laser arrays, where disorder of one type mitigates (and overcomes) the desynchronization effects due to a different disorder source [N. Nair, K. Hu, M. Berrill, K. Wiesenfeld, and Y. Braiman, Phys. Rev. Lett. 127, 173901 (2021)]. In our presentation, we will elaborate on mechanisms whereby the addition of disorder enhances system-wide coherence and demonstrate computational and experimental evidence of such an effect. Specifically, we will analyze the dynamics of an array of single-mode semiconductor diode lasers, which has been shown experimentally to generate a high degree of phase coherence. We will present examples of how one type of disorder mitigates array desynchronization shaped by a different type of disorder and generates a highly ordered dynamical state.

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MS15

Crowd Heterogeneity-Induced Instabilities of Footbridges

Despite significant interest among engineers and applied mathematicians, the interaction between walking pedestrians and lively bridges has still not been well understood. The key question is whether human-to-human interaction is a key ingredient of the bridge instability mechanism or human-to-bridge interaction is sufficient. In this talk, we will demonstrate that human-to-human interactions of heterogeneous pedestrians can trigger an instability of a bridge more effectively than crowds of identical pedestrians. We will also discuss the role of crowd heterogeneity in possible phase pulling between the pedestrians and bridge motion.

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MS15

Heterogeneity in the Synchronization Dynamics of Ants

Rhythm synchronization is a collective behavior that is often observed in social animals. Despite the pervasiveness of social rhythm synchronization, there is limited empirical data on the extent and role of behavioral heterogeneity in synchronizing animal groups. Ants are an excellent model group to investigate this topic because several species are known to exhibit highly periodic, collective cycles of activity where the ants inside a nest will rest and awaken together in predictable intervals. Here, I summarize work done on this phenomenon. I present a large comparative dataset of activity patterns obtained from isolated individuals, small groups, and entire colonies from more than 20 ant species and demonstrate the existence of substantial intraspecific and interspecific heterogeneity for both individuals and colonies. I also show that the oscillation frequency of colonies has evidence of phylogenetic signal; the collective oscillations of closely related species are more alike than distantly related species. Lastly, I assess what impacts individual-level heterogeneity might have on the ability of a group of ants to synchronize and how such heterogeneity might influence the evolvability of synchronization in animals.

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MS15

Converse Symmetry Breaking in Network Dynamics

An increasing number of systems is now known to exhibit a symmetry effect that we refer to as converse symmetry breaking (CSB). It concerns scenarios where the stabilization of a symmetric state of interest requires explicitly breaking the given symmetry in the system itself. In this presentation, I will discuss recent advances in the mathematical, computational, and experimental study of this effect in the synchronization of coupled oscillators. In this case, CSB describes situations where stable synchronization requires the oscillators to be nonidentical, nonidentically coupled, or nonidentically driven. Examples will be given for networks of optoelectronic, electromechanical, and electrochemical entities as well as power generators and chaotic circuits, among others. It follows that parameter mismatches, which are ubiquitous and often unavoidable in real systems, can serve as a source of stability.

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MS16

Development of Accurate and Tractable Edmd Approximations for Analysis and Control

The Koopman operator is a theoretical framework that allows the use of linear analysis tools on transformations of nonlinear systems. Unfortunately, the analytical transformation of an arbitrary system is only possible for a specific family of unforced polynomial systems. To solve the problem of not having analytical transformations, some numerical-decomposition methods; related to the eigenvalues and eigenvectors of the differential equation field, can give a truncated approximation of the Koopman spectrum. For some of these decompositions, part of the method consists in the formulation of a set of functions of the state of the system, and subsequently, find a relation between the linear-time evolution of the functions and the nonlinear-time evolution of the state. To get better approximations of the dynamics in the function space; of smaller order and dimension, and improve the chances of getting the Koopman operator, it is important to have a proper selection of the observables, and carefully track the numerical stability of the algorithm.

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MS16

Exact Koopman Forms in the Presence of External Inputs

The Koopman framework offers a linear representation of finite-dimensional nonlinear systems through a generally infinite dimensional embedding. The Koopman formalism has originally been introduced for autonomous systems. However when developing models for control applications, the presence of external inputs in the model is often desired. The continuous-time system case with a linear or a control affine input form has recently been discussed. However, the discrete-time system case has not yet been addressed. Practically, a linear time-invariant (LTI) Koopman form is predominantly assumed without theoretical support, as it facilitates the use of linear quadratic regulation and model predictive control techniques. This contribution investigates and derives lifted forms under inputs for a general class of nonlinear systems in both continuous and discrete time. We prove, through the fundamental theorem of calculus, that the resulting lifted representations give linear state-space Koopman models with a state (and input, for the discrete-time case)-dependent input matrix. This theoretical insight greatly helps during system identification using Koopman models, especially when performing model selection, as well as when making a proper choice for LTI or linear parameter-varying techniques for the control of nonlinear systems through the Koopman approach.

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MS16

A Data-Driven Approach to Stability Using the Koopman Operator

In this talk, we leverage the Koopman framework to provide a novel method for data-driven stability analysis. We are given a set of data points generated by a dynamical system whose origin is a stable equilibrium, and we aim at estimating the stability region of this equilibrium. To do so, we construct a candidate Lyapunov function for the data-driven approximation of the Koopman operator and estimate its validity region from the data. Then an inner approximation of the stability region is given by the largest sublevel set of the Lyapunov function that lies within the validity region. The method will be illustrated with several examples and the use of the probabilistic scenario approach will be discussed in the case of high-dimensional systems.

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MS16

Learning Bilinear Models of Actuated Koopman Generators from Partially-Observed Trajectories

Data-driven models for nonlinear dynamical systems based on approximating the underlying Koopman operator or generator have proven to be successful tools for control. It has become well known that the Koopman generators for control-affine systems also have affine dependence on the input, leading to finite-dimensional bilinear approximations of the dynamics. Yet there are still two main obstacles that limit the scope of current approaches for approximating the Koopman generators of systems with actuation. First, the performance of existing methods depends heavily on the choice of basis functions over which the Koopman generator is to be approximated. Secondly, if we do not observe the full state, we may not gain access to a sufficiently rich collection of such functions to describe the dynamics. This is because the commonly used method of forming time-delayed observables fails when there is actuation. To remedy these issues, we write the dynamics of observables governed by the Koopman generator as a bilinear hidden Markov model, and determine the model parameters using the expectation-maximization (EM) algorithm. We demonstrate the performance of this method on three examples, including recovery of a finite-dimensional Koopman-invariant subspace for an actuated system with a slow manifold; estimation of Koopman eigenfunctions for the unforced Duffing equation; and model-predictive control of a fluidic pinball system based only on noisy observations of lift and drag.

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MS17

Highly Ordered Stripes and Spatially Extended Dislocations Produced by the Dispersive Swift-Hohenberg Equation

Motivated by previous results showing that the addition of a linear dispersive term to the Kuramoto-Sivashinsky equation produces spatially extended dislocations called seam defects, we study the Swift-Hohenberg equation with an added linear dispersive term, the dispersive Swift-Hohenberg equation (DSHE). The DSHE also exhibits seam defects, but, in contrast to the Kuramoto-Sivashinsky equation, the DSHE has a narrow band of unstable wavelengths close to an instability threshold. This allows for analytical progress to be made. We show that the amplitude equation for the DSHE close to threshold is a special case of the anisotropic complex Ginzburg-Landau equation (ACGLE) and that seams in the DSHE correspond to spiral waves in the ACGLE. Seam defects and the corresponding spiral waves tend to organize themselves into chains, and we obtain formulas for the velocity of the spiral wave cores and for the spacing between them. In the limit of strong dispersion, a perturbative analysis yields a relationship between the amplitude and wavelength of a stripe pattern and its propagation velocity. Numerical integrations of the ACGLE and the DSHE confirm these analytical results.

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MS17

Measures of Order for Imperfect Two-Dimensional Patterns

Motivated by patterns with defects in natural and laboratory systems, we develop two quanti- tative measures of order for imperfect Bravais lattices in the plane. A tool from topological data analysis called persistent homology combined with the sliced Wasserstein distance, a metric on point distributions, are the key components for defining these measures. The measures generalize previous measures of order using persistent homology that were applicable only to imperfect hexag- onal lattices in two dimensions. We illustrate the sensitivities of these measures to the degree of perturbation of perfect hexagonal, square, and rhombic Bravais lattices. We also study imperfect hexagonal, square, and rhombic arrangements of nanodots produced by numerical simulations of pattern-forming partial differential equations. These numerical experiments serve to compare the measures of lattice order and reveal differences in the evolution of the patterns in different partial differential equations.

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MS17

Can We Characterise Spatial Localisation of Patterns Using Persistence Homology?

Techniques based on symmetry which consider the dynamics of slowly decaying modes help to analyse and predict the formation of patterns in domains comparable to the scale of the pattern. However, a complete quantitative characterisation of patterns formed in domains that are much larger than the scale of the pattern is still an open challenge. One complicating reason is that when patterns form in extended domains, spatial localisation, i.e., where a pinned front separates two differently patterned states within the domain, becomes possible. In higher dimensions and in systems with more than one preferred length-scale, multiple branches of spatially localised states with different symmetries can be obtained over a given parameter range. A spectral measure (Fourier transform) alone cannot distinguish between all such states. In this work we use persistent homology to track changes in the number of components in a pattern and obtain a multi-scale topological signature in the form of a persistence diagram. We then use a metric (Wasserstein) to quantitatively characterise distances between persistence diagrams. This approach will allow us to characterise spatially localised states with different symmetries and to explore how additional structure is added along a solution branch of spatially localised states.

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MS17

Weak Diffusive Stability Induced by High-order Spectral Degeneracies

The Lyapunov stability of equilibria in dynamical systems is determined by the interplay between the linearization and nonlinear terms. In this talk, we present our recent results on the case when the spectrum of the linearization is diffusively stable with high-order spectral degeneracy at the origin. Roll solutions at the zigzag boundary of the Swift-Hohenberg equation are shown to be nonlinearly stable, serving as xamples that linear decays weaker than the classical diffusive decay, together with quadratic nonlinearity, still give nonlinear stability of spatially periodic patterns. The study is conducted on two physical domains: the 2D plane and the infinite 2D torus. Linear analysis reveals that, instead of the classical t^{-1} diffusive decay rate, small perturbations of zigzag stable roll solutions decay with slower algebraic rates ($t^{-3/4}$ for the 2D plane; $t^{-/4}$ for the infinite 2D torus) due to the high-order degeneracy of the translational mode at the origin in the Bloch-Fourier spaces. The nonlinear stability proofs are based on decompositions of the neutral translational mode and the faster decaying modes, and fixed-point arguments, demonstrating the irrelevancy of the nonlinear terms.

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MS18

Sample-Efficient Reinforcement Learning Through Trajectory Generation

A key barrier to using reinforcement learning (RL) in main real-world applications is the requirement of a large number of system interactions for exploration. Offline RL has been proposed to reduce the number of interactions with the physical environment by learning control policies from past data. However, its performance suffers from the lack of exploration and the distributional shifts in trajectories induced by updated control policies. Moreover, most offline RL methods require that all system states be directly observable, which is difficult to attain for many applications. To overcome these challenges, we propose a sample-efficient

RL algorithm through trajectory generation, where the distribution is adaptive to updated control policies and different ranges of explorations. Motivated by the fundamental lemma for linear systems with conditions for sufficient excitation, we generate trajectories from the linear combination of historical trajectories. For a class of control policies, we rigorously prove that the algorithm generates trajectories with the exact distribution as if they are sampled by interacting with the real system. In particular, the algorithm extends to systems where the states are not directly observable. On this basis, we generalize the algorithm to nonlinear systems with kernelized representations. Experiments show that the proposed method significantly reduces the number of sampled data needed for RL algorithms.

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MS18

A Neural Network Ensemble Approach to System Identification

We present a new algorithm for learning unknown governing equations from trajectory data, using an ensemble of neural networks. Given samples of solutions $x(t)$ to an unknown dynamical system $\dot{x}(t) = f(t, x(t))$, we approximate the function f using an ensemble of neural networks. We express the equation in integral form and use Euler method to predict the solution at every successive time step using at each iteration a different neural network as a prior for f. This procedure yields M-1 time-independent networks, where M is the number of time steps at which $x(t)$ is observed. Finally, we obtain a single function $f(t, x(t))$ by neural network interpolation. Unlike our earlier work, where we numerically computed the derivatives of data, and used them as target in a Lipschitz regularized neural network to approximate f, our new method avoids numerical differentiations, which are unstable in presence of noise. We test the new algorithm on multiple examples both with and without noise in the data. We empirically show that generalization and recovery of the governing equation improve by adding a Lipschitz regularization term in our loss function and that this method improves our previous one especially in presence of noise, when numerical differentiation provides low quality target data. We compare our method with other methods for system identification and combine our proposed architecture with SINDy to produce an accurate and interpretable result.

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MS18

Random Feature Models for Learning Interacting Dynamical Systems

We will discuss a sparse random feature method with applications to learning interaction equations from trajectory data. We will provide an overview of our theoretical results on the concentration of these random feature matrices, the connections to generalization and complexity bounds, and the design and applications of the method.

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MS18

Learning Particle Dynamics from Observations of Ensembles with Physics-Informed Deep Generative Models

We propose a new method for inferring the governing stochastic ordinary differential equations (SODEs) by observing particle ensembles at discrete and sparse time instants, i.e., multiple snapshots. Particle coordinates at a single time instant, possibly noisy or truncated, are recorded in each snapshot but are unpaired across the snapshots. By training a physics-informed generative model that generates fake sample paths, we aim to fit the observed particle ensemble distributions with a curve in the probability measure space, which is induced from the inferred particle dynamics. We employ different metrics to quantify the differences between distributions, e.g., the sliced Wasserstein distances and the adversarial losses in generative adversarial networks. We illustrate the method by learning the drift and diffusion terms of particle ensembles governed by SODEs with Brownian motions and Lvy processes up to 100 dimensions. We also discuss how to treat cases with noisy or truncated observations. Apart from systems consisting of independent particles, we also tackle nonlocal interacting particle systems with unknown interaction potential parameters by constructing a physics-informed loss function.

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MS19

Effect of Household Structure in Measles Transmission

Households play a key role in transmission of infectious diseases. Contacts within households are stronger and more sustained resulting in higher transmission potential for infectious disease. We introduce a household transmission model of measles that includes demographic changes to capture evolution of households and dynamics of disease transmission therein. In our model of the transmission of measles, we assume homogeneous mixing of individuals within the household and age-structured mixing outside the household. We explore how different assumptions relating to distribution of household sizes can change the dynamics of measles transmission and infection pattern of the disease.

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MS19

Temporal and Probabilistic Forecasts of Epidemic Interventions

Forecasting disease spread is a critical tool to help public health officials design and plan public health interventions. However, the expected future state of an epidemic is not necessarily well defined as disease spread is inherently stochastic, contact patterns within a population are heterogeneous, and behaviors change. In this work, we extend the approach of Noël *et al.* [Phys. Rev. E, 79(2), 026101 (2009)] and use time-dependent probability generating functions (PGFs) to capture these characteristics by modeling a stochastic branching process of the spread of a disease over a network of contacts while public health interventions are introduced over time. To achieve this, we define a general transmissibility equation to account for varying transmission rates, recovery rates, contact patterns and percentage of the population immunized. The resulting framework allows for a temporal and probabilistic analysis of an intervention's impact on disease spread, and match continuous-time stochastic simulations which more computationally expensive. To guide policy making, we then define several metrics over which temporal and probabilistic intervention forecasts can be compared. Given that epidemics do not always follow their average expected trajectories and that the underlying dynamics can change over time, our work paves the way for more detailed short-term forecasts of disease spread and more informed comparison of intervention strategies.

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MS19

Capturing Complex Contagion Processes on Higher Order Networks

Complex contagion processes refer to spread algorithms in which successful transmission depends on non-trivial local neighborhood conditions (e.g., thresholds in the number, or percent, of direct contacts infected). Expressing these conditions in traditional dyadic networks can be awkward. One of the natural options is therefore to switch notational system to focus instead on higher-order systems (e.g., hypergraphs or simplicial sets). In this talk, we will discuss a simple formulation for functions that operate on simplices and therefore provide a very natural way to evaluate and predict the behavior of complex contagion processes that rely on local neighborhood properties. We will also discuss when these formulations critically depart from standard tools of topological data analysis by violating the assumptions of downward closure.

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MS19

A Generating-Function Approach to Modelling Complex Contagion on Clustered Networks Using Multi-Type Branching Processes

Understanding cascading processes on complex network topologies is paramount for understanding how diseases, information, fake news and other media spread. Complex contagion is one such cascading process which is characterised by repeated exposures making adoption more likely. Complex contagion dynamics have been observed in the adoption of health behaviour online [1], among other contexts. Clustering; i.e., the extent to which "a friend of my friend is a friend of mine", drives the complex contagion. In this talk, we extend the multi-type branching process method for modelling complex contagion on clustered networks developed in Keating et al., 2022 [2], which relied on homogenous network properties, to a more general class of clustered networks and, using a model of socially-inspired complex contagion, we obtain results, not just for the average behaviour of the cascades but, for full distributions of the cascade properties. References: [1] D. Centola, The spread of behavior in an online social network experiment, Science, 329 (2010), pp. 11941197. [2] L. A. Keating, J. P. Gleeson, and D. J. P. OSullivan, Multitype branching process method for modeling complex contagion on clustered networks, Physical Review E, 105 (2022), p. 034306.

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MS20

Space Embedded Graphon Mean Field Games

An (embedded) vertexon in a connected compact m-dimensional set M is defined to be the vertex set of a graph together with an asymptotically dense partition hierarchy of M. Sequences of vertexons have subsequential vertexon limit measures in M independent (within a large class) of the partition hierarchy chosen. Consequently, when vertexon limit measures have densities, the differentiation of functions on open sets within their support is well defined. Further, along convergent subsequences, the associated graphs have subsequential graph edge limit measures in M X M termed embedded graphons, or graphexons. In analogy with Graphon Mean Field Games (GMFGs), Embedded GMFGs are defined on open vertexon sets. Differentiation with respect to vertexon node location then permits the definition of critical nodes to be those where Nash value functions for an associated EGMFG is stationary with respect to node position. In particular cases, maximal critical nodes are shown to be located at (generalized) maximal degree nodes in the graphexon. A further feature of vertexon limits is that they provide a form of node population density which extends the large nodal agent population aspect of EGMFG systems.

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MS20

Graphon Control and Graphon Analysis for Large Networks of Dynamical Systems

Graphon control has been proposed and developed (SG, PEC 2017-2021) to approximately solve control problems for very large-scale networks of linear dynamical systems based on their associated graphon limits. In this talk, we first summarize the graphon control methodology in controlling arbitrary-size networks of linear control systems. Then we present the applications of graphon spectral decompositions in graphon control and graphon mean field games. Finally, the notion of fixed-point centrality for graphs and graphons in quantifying nodal importance for networks of dynamical systems will be outlined. The presentation is based on joint work with Peter E. Caines.

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MS20

Mean-Field Limits: From Complex Networks to Adaptive Higher-Order Systems

Network dynamics in complex systems can often only be treated analytically in large-node limits leading to mesoscopic/kinetic or to macroscopic PDE. In my talk, I am going to outline techniques, how to include a broad range of heterogeneous network structures into kinetic Vlasov-type PDEs. In particular, also the cases beyond graphons, for adaptive and hypergraph systems will be covered. From these limit PDEs, a wide range of dynamics can then be proven analytically. A key new technique that will be explained is the use of graphops (”graph operators”).

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MS20

Exploring Pattern Formation in the Kuramoto Model on Graphs

Biological and physical oscillators, ranging from fireflies, to neurons, to power-grid networks, often exhibit collective dynamics. The Kuramoto model is a nonlinear dynamical system widely used to explore synchronization and pattern formation in many such systems. We study the effects of both network structure and the distribution of intrinsic frequencies on the types of patterns that form in this model. In the mean field limit, the resultant graphons carry information about the underlying networks and allow for easily interpretable stability and bifurcation analysis. This work is in collaboration with Hayato Chiba and Georgi Medvedev.

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MS21

Utilizing Metastability to Design a Testbed for a Data-Driven Estimation of Resilience in Networked Dynamical Systems

Complex networks composed of FitzHugh-Nagumo oscillators are known to exhibit a rich variety of dynamical behaviors, including recurrent extreme events. We utilize such networks to develop a toy model of a multistable system that is capable of self-generating transitions between various states (dynamical regimes). Various control parameters allow us to modify resilience of the multistable networked dynamical system in a controlled manner. We analyze multivariate time series of the system's observables to evaluate the suitability of a recently proposed data-driven estimator of resilience that specifically probes temporal chanages of the network's coupling structure. In this talk, we report first findings for the resilience estimator.

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MS21

Coping with Transient Chaos in Excitable Media

The spatiotemporal dynamics of excitable media may be governed by chaotic transients. We present examples of this kind of transient chaos in the 2D FentonKarma model describing the propagation of electrical excitation waves in cardiac tissue. Using numerical simulations it is shown how the average duration of chaotic transients depends on model parameter values and other characteristics like the dominant frequency, the size of the excitable gap, pseudo ECGs, the number of phase singularities and parameters characterizing the action potential duration restitution curve. These quantities are used to predict the average transient time of chaotic wave dynamics using polynomial regression. Furthermore, the effects of heterogeneities on the duration of transients as well as methods to control transient lifetime are discussed.

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MS21

Metastability and Rate-Induced Tipping in Brain Stimulation from the Curse of Joule to Siberian Peat Fires

All electric and magnetic stimulation of the brain deposits thermal energy in the brain. This occurs through Joule heating of the conductors carrying current through electrodes or magnetic coils, or through dissipation of energy in the resistive brain. Magnetic induction lets us separate Joule heating from induction effects by contrasting AC and DC driving of magnetic coils using the same energy dissipation. Since mammalian neurons have no sensitivity to static magnetic fields, and if there is no effect on spike timing to oscillating magnetic fields, we presume that induced electrical currents within the brain are below the molecular shot noise where interaction with tissue is purely thermal. We examined frequencies produced from micromagnetic coils operating below the shot noise threshold for neurons. Small temperature increases and decreases of 1oC caused consistent transient suppression and excitation of neurons during temperature change. Modeling the biophysics demonstrated that the Na-K pump, and to a lesser extent the Nernst potential, accounts for these transient effects. Such effects depend upon compartmental ion fluxes and the rate of temperature change. We note a remarkable similarity of these physics with other thermal rate-dependent tipping points in planetary warming dynamics. These experimental and theoretical findings demonstrate that stimulation of the brain must account for small thermal effects that are always present in electrical and magnetic stimulation.

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MS21

Acetylcholine, Network Dynamics and Memory Consolidation

Neuromodulation alters brain dynamics on the timescales far slower that the time required for neural computation, however it can drastically change circuit dynamics underlying information processing in the brain, and thus its outcomes. Here we will focus on endpoints of neuromodulatory effects of acetylcholine (ACh) and the role it can play in altering brain dynamics, and its specific functions in state dependent memory consolidation. Specifically, we will connect experimental findings with the developed modeling framework to identify how ACh affects the excitation properties of individual cells as well as those of hippocampal circuits as a whole. Then, we will continue to show how these properties modulate network-wide dynamics and finally hypothesize how these effects mediate reorganization of memory representations and differential roles of NREM and REM play in this process.

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MS22

Fractional Diffusion in Cardiac Models

Heart disease is the leading cause of mortality in the US and while there exist many treatments to aid cardiovascular problems. Alternans of the heart's action potential has been shown to be a dangerous marker for mortality with over 80% of people identified with it dying within 2 years if not treated. Experimental studies have shown how alternans in space can lead to the initiation of complex arrhythmias because of the spatiotemporal dispersion in refractoriness they produce. Computational studies have shown mechanisms behind the dynamics of alternans, however to date they fail to reproduce the dynamics quantitatively, requiring much larger tissue domains compared with experiments. In this talk we argue that the voltage propagation in cardiac tissue in the mesoscopic scale can be described by fractional diffusion and this allows for models to be fitted in tissue sizes as in experiments.

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MS22

Building a Statistical Mechanics Based Model of IP3 Regulation

The IP3 receptor is responsible for regulating calcium release in cardiac cells and has the potential to cause cardiac arrhythmias by disrupting calcium cycling. However, there is still incomplete understanding of how various ligands regulate IP3. The most recent Cryo-EM studies have revealed that this channel is comprised of multiple domains that are allosterically coupled, and that the interaction between these domains is regulated by calcium and IP3. However, there is currently no computational model available that can fully account for the allosteric regulation of a macromolecule made up of multiple cooperative domains. In this presentation, I will discuss our recent efforts to explore the statistical mechanics of allosteric regulation of these channels, aiming to gain a better understanding of the ligand regulation of these receptors.

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MS23

Modelling of Spatial Infection Spread Through Heterogeneous Population: From Lattice to PDE Models

We present a simple model for the spread of an infection that incorporates spatial variability in population density. Starting from first principle considerations, we explore how a novel PDE with state-dependent diffusion can be obtained. This model exhibits higher infection rates in the areas of higher population density, a feature that we argue to be consistent with epidemiological observations. The model also exhibits an infection wave whose speed varies with population density. In addition, we demonstrate the possibility that an infection can jump (i.e., tunnel) across areas of low population density towards the areas of high population density. We briefly touch upon the data reported for coronavirus spread in the Canadian province of Nova Scotia as a case example with a number of qualitatively similar features as our model. Lastly, we propose a number of generalizations of the model towards future studies. Joint work with Arvin Vaziry and Panos Kevrekidis.

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MS23

Extreme Statistics and Ovarian "Oversupply"

Why are women born with hundreds of thousands of primordial follicles when only a few hundred will ever ovulate a mature egg? In this talk, we use slowest first passage time theory to explain this ovarian "oversupply.' We show that primordial follicle oversupply and stochastic growth activation yield a steady supply of growing follicles that lasts for several decades of fertility. Further, we show that the supply of growing follicles is robust to a variety of perturbations and the timing of fertility cessation (menopause age) is tightly controlled. Though stochasticity is often viewed as an obstacle in physiology and primordial follicle oversupply has been called "wasteful,' this analysis suggests that oversupply and stochastic growth activation function together to ensure robust and reliable female reproductive aging.

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MS23

Discovering RNA Dynamic Rates from Spatial Stochastic Snapshots

There are unresolved mysteries about the dynamics of RNA splicing, an important molecular process in modulating gene expression. These uncertainties remain because the obtainable data are not of the dynamics themselves, but rather static spatial images of cells with stochastic particles. From a modeling perspective, this creates a challenge of finding the right mathematical description that respects the stochasticity of individual particles but remains computationally tractable. Ill share our approach of constructing a spatial Cox process with intensity governed by a reaction-diffusion PDE. Theory and practice of inferring dynamic rates from experimental images will be discussed, including the use of variational Bayesian inference techniques. Several outstanding issues remain about how to combine statistical and data-science approaches with more exotic mechanistic models of spatial stochastic systems in biology. This work is in collaboration with the Ding lab of Biomedical Engineering at UCI.

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MS23

Diffusion on Dynamical Networks with Applications to Cell Biology

The transport of particles in cells is influenced by the properties of intracellular networks they traverse while searching for localized target regions or reaction partners. Moreover, given the rapid turnover in many intracellular structures, it is crucial to understand how dynamical changes in the network structure affect diffusive transport. In this work, we use network theory to characterize complex intracellular biological environments across scales. We develop both a coarse-grained model and an efficient computational method to compute the mean first passage times for simulating a particle diffusing along two-dimensional planar networks extracted from fluorescence microscopy imaging. We first benchmark this methodology in the context of synthetic networks, and subsequently apply it to live-cell data from endoplasmic reticulum tubular networks.

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MS24

Data Driven Model Discovery and Interpretation for Car T-Cell Killing Using Sparse Identification and Latent Variables

In the development of cell-based cancer therapies, quantitative mathematical models of cellular interactions are instrumental in understanding treatment efficacy. Efforts to validate and interpret mathematical models of cancer cell growth and death hinge first on proposing a precise mathematical model, then analyzing experimental data in the context of the chosen model. In this work, we present the first application of the sparse identification of non-linear dynamics (SINDy) algorithm to a real biological system in order discover cell-cell interaction dynamics in in vitro experimental data, using chimeric antigen receptor (CAR) T-cells and patient-derived glioblastoma cells. By combining the techniques of latent variable analysis and SINDy, we infer key aspects of the interaction dynamics of CAR T-cell populations and cancer. Importantly, we show how the model terms can be interpreted biologically in relation to different CAR T-cell functional responses, single or double CAR T-cell-cancer cell binding models, and density-dependent growth dynamics in either of the CAR T-cell or cancer cell populations. This data-driven model-discover based approach has the potential to improve the implementation and efficacy of CAR T-cell therapy in the clinic through an improved understanding of CAR T-cell dynamics.

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MS24

Mathematical Modeling of CAR-T Cells for HIV-Cure

Antiretroviral therapy (ART) suppresses human immunodeficiency virus (HIV) levels in the blood to below detection limits in standard assays. However, ART must be taken daily due to a latent reservoir of long-lived, HIV-infected cells that prevent cure. The five known cases of HIV cure have resulted from people with HIV receiving allogeneic hematopoietic stem cell transplantation (HSCT) from donors with mutations in the CCR5 genes, granting protection from HIV infection to donor cells. One additional possible driver for the reduction of latently infected cells is the graft-vs-reservoir (GvR) effect, where T cells from the donor kill HIV-infected cells in the recipient. One ongoing approach to reproduce this effect without transplantation is to use T cells with HIV-specific chimeric antigen receptors (CAR) to boost the immune system. Ongoing pilot studies give CAR T cell infusions during ART to Simian-HIV (SHIV)-infected non-human primates (NHP) to induce post-rebound control after ART is interrupted. We have developed ordinary differential equation models that recapitulate plasma viral load and CAR T cell measurements from SHIV-infected NHP receiving CAR T cells and controls. We simulated each data-validated model to find optimal conditions in which this strategy provides ART-free SHIV remission. Although gene and cell therapy strategies for HIV cure are in the initial stages, mathematical modeling might contribute to accelerating the success of these approaches.

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MS24

Modelling the Role of T-Regulatory Cells on Relapse Following Car T-Cell Therapy

Immunotherapies are a new class of cancer treatments that focus on bolstering the immune system's ability to fight cancer. Chimeric Antigen Receptor (CAR) T-cell therapy is a type of immunotherapy that has proven very successful in patients with relapsed B-Cell Acute Lymphoblastic Leukemia (B-ALL). We develop an ordinary differential equation model of CAR T-cell therapy for B-ALL including T-regulatory cells and demonstrate that it can explain relapse in the absence of CAR T-cells.

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MS24

Modeling Local Administration of CAR T-cell Therapy for Solid Tumors

Chimeric antigen receptor (CAR) T-cell therapy's success treating hematologic malignancies has generated widespread interest in translating this technology to target solid cancers. To date, CAR T-cells are typically administered to patients systemically, in the bloodstream. However, multiple studies targeting solid tumors propose local administration directly into the tumor or at the tumor site to increase CAR-T-cell infiltration and thereby improve treatment outcomes. In this work, we develop a reaction-diffusion model for CAR T-cell treatment of solid tumors via local administration. We validate the model results against data from imaging studies of local administration of CAR T-cells in a mouse model. We use numerical simulations to compare the effect of introducing CAR T-cells via intratumoral injection versus intracavitary administration when treating tumors with varying proliferation rates and diffusiveness. Our results suggest that locally administered

CAR T-cells are most successful against low-proliferation, high diffusivity tumors, which have the lowest average density, not tumors with both low proliferation and low diffusivity which have the smallest total tumor burden and the highest volume doubling time. These findings affirm the clinical observation that CAR T-cells will not perform equally across different types of solid tumors.

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MS25

An Application of Converse KAM to Flux Surfaces for Toroidal Magnetic Configurations

A method to establish regions of 3D space through which pass no invariant 2-tori transverse to a given direction field is applied to the analysis of helical perturbations of axisymmetric toroidal vector fields. It finds regions corresponding to magnetic islands and chaos for the fieldline flow. Minimization of these regions is proposed as tool to help in the design of plasma confinement devices of the Tokamak and Stellarator type.

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MS25

Weighted Birkhoff Averages: a Tool to Identify Invariant Tori in Hamiltonian Systems

We investigate the utility of using a weighted Birkhoff average (WBA) for distinguishing between regular and chaotic orbits for the two-wave Hamiltonian system, a model for magnetic field line flow and a quasiperiodically forced, dissipative system that has a strange attractor with no positive Lyapunov exponents. We extend previous results that applied the method to maps, showing that the WBA can be super-convergent for flows when the system and function are C^{∞} and the dynamics is conjugate to a rigid rotation with Diophantine rotation vector. We investigate how the accuracy attained depends on choice of phase space function, orbit length and weight function width. In practice the averages are shown to achieve machine precision for quasiperiodic orbits for an integration time of $O(10^3)$ periods. The relatively slow convergence of chaotic trajectories allows an efficient discrimination criterion.

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MS25

Level Set Learning for Poincare Plots of Symplectic Maps

Many important qualities of plasma confinement devices can be determined via a Poincar plot of a symplectic return map. These qualities include the locations of periodic orbits, magnetic islands, and chaotic regions of phase space. However, every evaluation of the magnetic return map requires solving an ODE, meaning a detailed Poincar plot can be expensive to create. In this talk, we propose a kernel-based method of learning a single labeling function that is approximately invariant under the symplectic map. From the labeling function, we can recover the location of stable orbits, invariant circles, islands, and chaos. In addition, the labeling function can be found with relatively few evaluations of the underlying symplectic map, while being robust to error in the symplectic map evaluation.

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MS25

Rotation Vectors for Torus Maps by the Weighted Birkhoff Average

The weighted Birkhoff average is a numerical method that can be used to distinguish between chaotic regions, islands, and invariant tori, as well as to calculate the frequency vectors for these tori. We use this method to analyze the Arnold circle map. We then apply the method to higher-dimensional maps on tori, demonstrating the combination of chaos, periodic behavior, and resonant and nonresonant invariant tori. This allows us to consider the typical behavior for such maps, and observe how this behavior changes as we vary coupling parameters.

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MS26

Non-Collapse for the Lyapunov Spectrum of Dissipative Semilinear Problems with Applications to Passive Scalar Advection and to the Navier-Stokes Equations

Lyapunov exponents are the exponential growth rates of (stationary) compositions of linear operators, e.g.: the composition $A_n A_{n-1} \cdots A_1$ of an IID sequence of matrices $(A_i)_{i\geq 1}$; or the derivative $D_x f^n$ of the n-th iterate of a mapping $f : M \to M$ of a manifold M. I'll discuss in this talk the extension of these ideas to compositions of compact linear operators of an infinite-dimensional space, and how Lyapunov exponents are related to a variety of problems of fundamental interest in fluid mechanics, e.g., the Batchelor scale of a passively-advected scalar; and sensitivity with respect to initial conditions for solutions to the Navier-Stokes equations.

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MS26

Entropic Transfer Operators

We propose a new concept for the regularization and discretization of transfer 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 operator which can be analysed computationally. We prove that the spectrum of the discretized operator converges to the one of the regularized original operator, give a detailed analysis of the relation between the discretized and the original peripheral spectrum for a rotation map on the n-torus and provide code for 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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MS26

Consistent Spectral Approximation of Koopman Operators Using Resolvent Compactification

Koopman operators and transfer operators transform nonlinear dynamics in phase space to linear dynamics on vector spaces of functions, enabling the use of spectral techniques without modeling constraints such as linearity. The extraction of approximate Koopman eigenfunctions (and the associated eigenfrequencies) from an unknown system is nontrivial, particularly if the system has mixed or continuous spectrum. We discuss a spectrally-accurate approach to approximate the Koopman operator from data via a compactification of the resolvent of the Koopman generator. This approach employs kernel integral operators to approximate the skew-adjoint generator in measure-preserving systems by a family of skew-adjoint operators with compact resolvent, whose spectral measures converge in a suitable asymptotic limit, and whose eigenfunctions are approximately periodic. We explore implementations of this technique using data from several different example systems including Lorenz 63.

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MS27

Pattern Formation Models for Cell Polarity, from Wave-Pinning to Localised Patterns

A class of four-component reaction-diffusion systems are studied in one spatial dimension which seek to capture the interaction between active and inactive forms of two G-protiens, known as ROPs in plants, thought to underly cell polarity formation. We first consider the case where the systems conserves total concentration of each ROP, which enables reduction to simple canonical forms when one seeks conditions for homogeneous equilibria or heteroclinic connections between them. Transitions between different forms and multiplities of such states are classiffied to using a novel form of catastrophe theory. For the time-dependent problem, the hetroroclinic connections represent so-called wave-pinned states that seperate regions with different ROP concentrations. It is shown numerically how the form of wave-pinning reached can be predicted, leading to a state diagram of different polairty forms as a function of initial total concentrations and system parameters. Second, we consider the effect of addition of source and loss terms, which leads to a completely different kind of dynamics involving localised patches governed by a homoclinic snaking mechanism. It is shown how interdigitated patterns are preferred to overlaid patterns, which is biologically plausible. A preliminary singular perturbation analysis in the limit as source and loss terms vanish is presented, as is ongoing work that extends the modelling to bulk-surface PDEs.

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MS27

Localized States in Active Fluids

Biological active matter is typically tightly coupled to chemical reaction networks affecting its assembly and stress generation. We show that localized states can emerge spontaneously if assembly of active matter is regulated by chemical species that are advected with flows resulting from gradients in the active stress. The localized patterns form at a subcritical instability and for parameter values for which patterns do not exist in absence of the advective coupling. They come in a large variety and also comprise localized oscillatory and chaotic states. Our work identifies a generic mechanism underlying localized cellular patterns.

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MS27

Modeling Contractility Patterns of Actomyosin Networks on Micropatterned Surfaces

Actomyosin network self-organization and contraction are central for cell organization, shape, and motility. The relative importance of active local stresses, network deformation, external adhesive global stresses, and geometry is still not well understood. We analyze in vitro experiments with reconstituted actomyosin networks on micropatterned surfaces of various shapes and adhesive patterns. These systems self-organize such that myosin rapidly condenses into a few spots, then a contraction process compacts the whole actin network. The compaction point is the center of homogeneous domains and biased to more adhesive regions of heterogeneous patterns. Experiments indicate the process is global, with a contraction pattern largely insensitive to myosin distribution. We model the actomyosin network as a 2D deformable viscoelastic cable-network material with active contractile stresses generated by myosin spots advected by the deforming network. The internal network forces are balanced by external drag forces from adhesions. Through analysis and simulation, we find that our model reproduces key experimental results. Notably, the model explains why the adhesion, not myosin, pattern determines the compaction point. Our findings shed light on the importance of mechanical and geometric (over biochemical) effects. Though contraction is local and randomly initialized, the external friction pattern and network connectedness lead to robust global behaviors on the cellular level.

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MS27

Emergence of Cell Chirality from the Spatial Organization of Actin and Myosin Cytoskeleton

The left-right asymmetry or chirality of the morphogenesis and arrangement of organ is essential for their function and development. The chirality of organ and tissue is derived from the chirality of cells, and the cell chirality emerges by organizing the molecular chirality within the cell. However, the principle of how molecular chirality is organized to lead to cell chirality is still unclear. To address this question, we experimentally study the chiral behaviors of single epithelial cells and provide a theoretical understanding of how the cell chiral arises from the molecular-level chirality. We first found that the nucleus rotates in the clockwise direction, which is driven by the actin and myosin cytoskeleton. During the rotation, the actin and myosin cytoskeleton organizes in a vortex-like chiral orientational order, which apparently drives the rotation. However, when the formation of stress fibers was repressed by drug treatment, the vortex-like chiral order disappeared and concentric achiral order emerged while the cells still rotate. Hence, the cell can rotate without any macroscopic chiral order of the cytoskeleton. To elucidate the mechanism of these chiral rotation, we analyzed a hydrodynamic model considering the effect of chirality of cytoskeleton. Our experiment and theory suggest that the cell chirality emerges as a collective behavior of chiral molecules even without any macroscopic chiral orientational order of the cytoskeleton.

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MS28

Data-Driven Polynomial Optimization for Dynamical Systems

Many important statements about dynamical systems can be proved by finding scalar-valued auxiliary functions whose time evolution along trajectories obeys certain pointwise inequalities 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 model-agnostic computational method that can be used to bound quantities of interest, develop optimal state-dependent feedback controllers, and discover invariant measures.

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MS28

Sparse Decompositions of Dynamical Systems with Applications to Sums-of-Squares Programming

For dynamical systems with certain sparse structures, we give sparse descriptions for several problems from nonlinear dynamical systems: region of attraction, maximum positively invariant set, attractor, invariant measures and Lyapunov functions. Our decomposition of the system is based on causal dependence in the dynamics between the different states. For computations, the proposed method pairs very well with sums-of-squares (SOS) programming where a reduction in the dimension implies a strong computational savings.

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MS29

Tipping Phenomena and Time Scales

Over the last decades, there is a growing concern about the crossing of tipping points in climate (sub)systems and ecosystems, which can lead to critical shifts towards less desirable alternative states of these systems. There are now also many theoretical studies, where tipping points are related to bifurcation in dynamical systems - often very simple models with few variables, timescales and/or no spatial component. By contrast, the real system is a large multi-scale system, meaning that there many temporal (and spatial) scales in play. In this talk, I will set the scene for the session and give an overview of the theory of tipping. Hereby I will focus on the importance of timescales. I will also show some situations in which time scale separation can either surprise or help us. For instance, the presence of very slow time scales can lead to arbitrarily late tipping point surprises, whereas time scale separation might allow us to study the cascading effects that the tipping of one system might have on another.

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MS29

Rigorous Criteria for Tipping and Tracking of Concave Coercive ODEs

This talk deals with rate- and size-induced tipping in nonautonomous scalar concave coercive differential equations. This class of problems is widely used in applied sciences. As an example and a motivation, we show the occurrence of rate-induced and size-induced tipping in simple locally concave models from climate science and neural network theory. The bulk of our results is, however, theoretical. We show that, for nonautonomous scalar concave coercive differential equations, the only possible bifurcation is the nonautonomous saddle-node bifurcation and that all tipping points occurring for these equations are in fact bifurcations of such type. Moreover, the detailed description of the critical transition is completed by rigorous and calculable criteria to identify the tipping and tracking scenarios without relying on the numerical approximation of locally pullback attractive solutions, an always troublesome task.

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MS29

Uncertainty Quantification for Tipping Points of the Atlantic Meridional Overturning Circulation

Climate change is one of the pressing complex systems challenges that society is concerned with. Subsystems of the earth might undergo critical transitions to a drastically different state under sustained global warming, i.e. pass a tipping point (TP). The tipping phenomenon is not restricted to climate science but also appears in epidemiology and ecology. One particular subsystem that has been identified to be at risk of tipping is the Atlantic Meridional Overturning Circulation (AMOC). It is of particular importance for the North Atlantic heat transport. The location and likelihood of its TPs depends on model parameters that may be poorly known. Reducing this parametric uncertainty is important to understand the likelihood of tipping behaviour. In this talk, I will present a methodology to obtain estimates for parametric uncertainty in a simple model of AMOC tipping, using a Bayesian inversion technique. Based on prior physical constraints, we come up with a posterior distribution of the model parameter that leads to a substantial narrowing of AMOC TPs. To visualise the impact of parametric uncertainty on TPs, we extend classical tipping diagrams by showing probabilistic bifurcation curves according to the inferred distribution of the model parameter. This allows the uncertain locations of TPs along the probabilistic bifurcation curves to be highlighted. Thereby, we contribute to an uncertainty quantification of high impact, low likelihood climate outcomes.

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MS29

Rate-Induced Tipping to Zombie Fires

Surface wildfires are generally believed to be the cause of so-called *Zombie fires* observed in peatlands, that disappear from the surface, smoulder underground during the winter, and "come back to life" in the spring. Here, we propose rate-induced tipping (R-tipping) to a *subsurface hot metastable state* in bioactive peat soils as a main cause of Zombie fires. Our hypothesis is based on a conceptual soil-carbon model subjected to realistic changes in weather and climate patterns, including global warming scenarios and summer heatwaves. Mathematically speaking, R-tipping to the hot metastable state is a nonautonomous instability, due to crossing an elusive *quasithreshold*, in a multiple timescale dynamical system. To explain this instability, we provide a framework that combines a special compactification technique with concepts from geometric singular perturbation theory. This framework allows us to reduce an R-tipping problem due to crossing a quasithreshold to a heteroclinic orbit problem in a singular limit. Thus, we identify generic cases of such R-tipping via: (i) unfolding of a codimension-two *heteroclinic folded saddle-node type-I singularity* for global warming, and (ii) analysis of a codimension-one *saddle-to-saddle hetroclinic orbit* for summer heatwaves, which in turn reveal new types of excitability quasithresholds.

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MS30

Inverse Moran Effect: Correlated Response to Uncorrelated Noise

The dynamics of many complex systems capable of synchronous behavior such as neural and ecological networks are strongly influenced by their environments. This influence can promote or disrupt synchronization. For example, correlated noise often enhances synchronization, as it allows the system to inherit order from its environment. In ecology, this idea is known as the Moran Effect and serves as a primary explanation for correlations in populations. Recently, it has been shown that for coupled limit-cycle oscillators, uncorrelated noise can enhance synchronization better than correlated noise under certain circumstances (Z.N. Nicolaou et al. Phys. Rev. Lett. 125, 094101 (2020)). By modifying a simple model for the Moran Effect, we show that a similar phenomenon arises even in the simplest coupled systems: systems that are linear and linearly coupled. In two dimensions, this inverse Moran Effect arises due to non-normality, while in higher dimensions, additional mechanisms emerge.

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MS30

Anharmonic Responses to Periodic Driving in Pattern-Forming Systems

Dissipative classical systems and quantum mechanical systems such as Faraday waves and time crystal phases can exhibit interesting temporal symmetry breaking phenomena. Recent studies have focused on subharmonic responses to periodic driving in which the system undergoes one oscillation every other driving period. Here, we demonstrate that such systems do not need to resonate in a subharmonic fashion but instead can also exhibit a continuously tunable anharmonic response to driving. This response emerges through a Neimark-Sacker bifurcation characterizing coresonance between modes in different branches of the dispersion relation and typically resulting in an incommensurate ratio between the resonant frequencies and the driving frequency. In this talk, I will demonstrate the anharmonic response in a model array of coupled pendula with alternating lengths and discuss ongoing work to design to fluid systems with anharmonic responses.

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MS30

Synchronization Induced by Designed and Random Heterogeneities in Electrochemical Oscillator Networks

It is widely held that identical systems behave similarly under comparable conditions. Yet, for systems that interact through a network, symmetry breaking often leads to scenarios in which this expectation does not hold, such as the lack of frequency synchrony for identical phase oscillator networks exhibiting chimera states. Here we demonstrate in a series of experiments with electrochemical oscillators that generic differences in oscillator properties that affect the natural frequencies can have beneficial effects on the extent of synchronization. Two examples are given, in which random or designed heterogeneities can enhance synchrony. In particular, we show that for a broad class of networks, asynchronous states can be converted into frequency synchronized states when otherwise identical oscillators are detuned to have different intrinsic frequencies. Frequency synchronization is achieved over a range of intrinsic frequency detuning and is thus a robust effect that does not depend on fine-tuning. These results, which are supported by simulations and theory, reveal a counterintuitive opportunity for parametric control of network dynamics that relies on exploiting system heterogeneity to produce robust behavioral homogeneity.

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MS30

Moving Spiral Wave Chimeras

In this talk, we investigate the properties of moving spiral wave patterns observed in discrete oscillatory media with nonlocal interaction. More specifically, we consider a two-dimensional array of heterogeneous nonlocally coupled phase oscillators with periodic boundary conditions and study the bound states of two counter-rotating spiral chimeras. Each spiral chimera is a spiral pattern with synchronized (coherent) spiral arms and a spatially randomized (incoherent) core. Unlike other known spiral chimeras with motionless incoherent cores, the two-core spiral chimeras typically exhibit drift motion. Due to this drift, their incoherent cores become spatially modulated and develop specific fingerprint patterns of varying synchrony levels. In the continuum limit of infinitely many oscillators, the two-core spiral chimeras can be studied using the Ott-Antonsen equation. This equation allowed us to identify three main classes of these chimeras: symmetric, asymmetric, and meandering spiral chimeras. Furthermore, we have computed a series of bifurcation diagrams that reveal the typical scenarios leading to the appearance of spiral chimeras and the relationship of these states to other patterns coexisting in the same oscillator system.

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MS31

Dictionary-Free Koopman Mpc with Nonlinear Input Transformation

This talk introduces a method for data-driven control based on the Koopman operator model predictive control. Unlike exiting approaches, the method does not require a dictionary and incorporates a nonlinear input transformation, thereby allowing for more accurate predictions with less ad hoc tuning. In addition to this, the method allows for input quantization and exploits symmetries, thereby reducing computational cost, both offline and online. Importantly, the method retains convexity of the optimization problem solved within the model predictive control online. Numerical examples demonstrate superior performance compared to existing methods as well as the capacity to learn discontinuous lifting functions.

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MS31

Optimal Control of Switched Koopman Models

While the application of Koopman operator theory to systems with continuous inputs has garnered a great deal of attention, less has been given to systems with a discrete set of inputs. For such systems, an input-dependent Koopman operator can be defined and approximately learned from data, for which the lifted observables follow the dynamics of a discrete-time switched linear system. We use such models for optimal control, minimizing a given cost function that we approximate as a linear combination of the Koopman observables. This optimization yields a value function that is piecewise affine on the lifted state space and can be computed recursively using principles of dynamic programming. However, this computation has exponential complexity in the horizon length, which motivates us to pursue suboptimal approaches that are computationally tractable. Our modeling and control approach is illustrated in the domain of arcade games. Such games typically have a varying numbers of on-screen entities and present a significant challenge for choosing appropriate state vectors. We propose the use of density-like observables, which we compute as the sum of kernel functions between screen pixels and fixed center points chosen via K-means clustering. The resulting Koopman models turn out to be effective at predicting game evolution. Moreover, optimal control policies designed to maximize the game score, produce notable improvement over random play.

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MS31

Koopman-Model Predictive Control with Signal Temporal Logic Specifications: Formulation and Case Study

Koopman-Model Predictive Control (MPC) is a novel technique in controlling nonlinear dynamical systems based on real-time optimization with successful applications in engineering and science. In safety-critical applications such as energy, mobility, and societal systems, richer specifications for behaviors of nonlinear systems must be considered beyond classical notions of stability and robustness. In this talk, we will present our recent research on the Koopman-MPC that can satisfy control specifications described by Signal Temporal Logic (STL), a temporal logic with semantics over finite-time signals in formal methods. The STL language can define rich time-dependent specifications for systems behaviors. Our formulation and case study in energy systems will be presented.

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MS32

Thermal Suppression of Wave Collapse.

An envelope model for short laser pulses is proposed. These pulses are short compared to fluid motion timescales and long compared to electron thermalization timescales. Numerical simulation of the thermal blooming of laser pulses at powers near the boundary of the self-focusing regime is presented in this model. The model includes terms representing the contributions of thermal blooming and the Kerr effect. In the context of the model, thermal blooming and the Kerr effect compete; Kerr driving and thermal blooming suppressing wave collapse. The dynamics of pulses whose energies are near the collapse threshold are numerically simulated.

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MS32

Proving Existence and Stability of Traveling Waves Using Rigorous Computation.

Using a combination of analytic and computer assisted methods of proof, we prove stability of traveling front solutions to the KdV-Burgers equation. The methods apply much more generally. In this talk we focus on the rigorous computations involved in the computer assisted methods of proof. We use a Newton-Kantorovich argument and the parametrization method to rigorously enclose the traveling wave profile and the Riccati equation. We use analytic interpolation of the ODE series solution coefficients in order to establish the result for values of the dispersion parameter ranging over an interval.

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MS32

Self-Similar Collapse to the NLS: A Bifurcation Analysis Approach

In this talk, we will focus on the self-similar collapse of the (1+1)-dimensional NLS equation with general nonlinearity exponent σ. Upon performing a dynamic rescaling on the NLS, we will present a general method that is capable of identifying self-similar waveforms as steady-state solutions in the so-called "co-exploding frame" for the NLS. Then, we will bring forth bifurcation analysis techniques as well as computational methods associated with them in order to perform a spectral stability analysis of the pertinent waveforms as a function of the nonlinear exponent σ. Most importantly, conclusions will be drawn about how the spectral picture in the co-exploding/self-similar frame connects with the one in the original frame. If time permits, connections with the identification of rogue waves as self-similar patterns will be discussed as well as recent advances on the generalized KdV equation.

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MS32

Stability Analysis of Solutions to the b-Family of Peakon Equations

The Camassa-Holm equation with linear dispersion was originally derived as an asymptotic equation in shallow water wave theory. Among its many interesting mathematical properties, which include complete integrability, perhaps the most striking is the fact that in the case where linear dispersion is absent it admits weak multi-soliton solutions - peakons' - with a peaked shape corresponding to a discontinuous first derivative. There is a one-parameter family of generalized Camassa-Holm equations, most of which are not integrable, but which all admit peakon solutions. Numerical studies reported by Holm and Staley indicate changes in the stability of these and other solutions as the parameter b varies through the family. In this talk, we describe analytical results on some of these bifurcation phenomena, showing that in a suitable parameter range there are stationary solutions - leftons' - which are orbitally stable. We establish information about the point spectrum of the peakon solutions and notably find that for suitably smooth perturbations there exists point spectrum in the right half plane rendering the peakons unstable for b¡1. We also show that the peakons are linearly unstable on L^2 for all values of b. Finally, we establish the orbital stability of the smooth solitary waves for $b > 1$.

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MS33

Acoustic Control of Microbubble Oscillations Using a Koopman Linear Quadratic Regulator

During the past decade, Koopman operator theory has gained prominence as a tool in data-driven dynamical systems, with applications in diverse fields of science and engineering. Here, we leverage recent work in Koopman control to design acoustic signals that drive microbubbles to oscillate as desired. We train a Koopman Linear Quadratic Regulator (K-LQR) on data for both spherical and non-spherical modes and then employ it for several novel control objectives. These include: (1) stabilization of the bubble at non-equilibrium radii; (2) forcing the volume mode to track arbitrary trajectories; (3) specifying the frequency content of the dynamic response. Preliminary work on controlling lipid-coated microbubbles and non-spherical shape modes is also presented. These results have applications for medical diagnostics using ultrasound contrast agents and for targeted drug delivery.

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MS33

Integrating Structural and Dynamic Functional Connectivity for Multidimensional Clinical Char-

acterizations

Connectivity data has become ubiquitous in computational neuroscience by allowing us to identify biomarkers of different neural processes and to discriminate between patient and control groups. While such methods have yielded novel and valuable insights into the brain, there remains a notable gap between the analytical strategies we are using and the complexity of the underlying problem. This talk will showcase recent work in my lab to predict complex behavioral deficits from brain connectivity data. This framework combines a model-based (generative) term, which learns key subnetworks in the brain, and a multivariate regression (predictive) term that uses the patient-specific contributions of these subnetworks to estimate behavioral manifestations. The key to this framework is the unified optimization procedure, by which the generative and predictive components directly influence each other. The blend of classical and AI methods also allows us to fuse multimodal and dynamic information to learn salient interactions from small sample sizes. We have validated this framework on a study of autism spectrum disorder, in which we simultaneously predict different behavioral impairments. Finally, I will conclude with snapshots of ongoing work in my lab that spans foundational, translational, and exploratory applications of machine learning for clinical neuroscience.

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MS33

Data-Driven State Criticality and Observability with Koopman Operator Methods

I will present two major results to show the use of data-driven Koopman methods to identify critical states and observable subspaces to solve problems in synthetic biology. In the first, I present the use of dynamic mode decomposition (DMD) to model the transcriptome-wide response of a root-isolate bacterium to a novel chemical compound. By solving an observability maximization problem for the DMD model, we find a panel of biomarkers that can act as effective biosensors for the compound, even in field studies with the bacterium. This study establishes a new precedent for reasoning about state criticality and system observability, even without prior knowledge of a network model. Second, I present new theoretical results that show how Koopman methods can be used to evaluate criticality of states to optimize performance of a nonlinear system. Historically, this problem is solved using either direct sensitivity analysis on a known model or by generating local function distributions that span the nonlinear observable subspace of a system. In the absence of a known model, I present a new Koopman-based method for estimating the observable subspace of a nonlinear system purely from data. Our results provide a route for data-driven discovery of critical states that affect an output-based performance measure.

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MS33
Multiomics of Dynamical Systems

Classical models of complex biological systems are represented by of differential equations. The analysis of such equations makes it possible to identify stationary points, their stability, phase portraits, parametric stability diagrams. Despite the era of big data, it is still useful to use low-dimensional systems of equations because they are interpretable, but still can describe the non-linear nature of biological systems and have inventive power: non-obvious relationships can be found, and thus new knowledge about the biological system can be created. On the other hand, advances in biotechnology are yielding new big data such as genomics, transcriptomics, and other omics. In the coming decades, a lot of work remains to be done on their analysis and interpretation - even the methods in this field are not sufficiently developed. Can we consider multiomics data as solution of some system of non-linear differential equations? Can we find examples of phase portraits or parametric stability diagrams among multiomic data? In this talk we consider several examples of how transcriptomic and proteomic data can be considered from the point of view of nonlinear dynamical systems.

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MS34
Modeling Misperception of Public Support for Climate Policy

Mitigating the consequences of climate change and reducing political polarization are two of the biggest problems facing society today. These problems are intertwined, since meeting international climate-mitigation targets requires implementing policies that accelerate the rate of decarbonization, and these policies can succeed only with widespread bipartisan support. Since the late 1980s, climate change has become a strongly polarizing issue in the United States. However, overall support for climate policy is high, with 66-80% of Americans supporting climate policies. Curiously, 80-90% of Americans underestimate public support for these policies, estimating the prevalence of support to be as low as 37-43%. (Sparkman et al. Nature communications 13.1 (2022): 4779.) The implications of such widespread misperception range from individual behaviors to legislative outcomes. Supporters of climate policy are more likely to self-silence if they believe their peers do not support it, and politicians are less likely to promote policies they believe to be unpopular. Here we present an agent-based social-network model of public perception of support for climate policy grounded in previous empirical studies and opinion surveys. We address the question of opinion misperception through an exploration of network structures and mechanisms of assessment of others' beliefs.

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MS34

A Bounded-Confidence Model of Opinion Dynamics with Heterogeneous Node-Activity Levels

Agent-based models of opinion dynamics examine the spread of opinions between entities and allow one to study phenomena such as consensus, polarization, and fragmentation. One examines them on social networks to investigate the effects of network structure on these phenomena. In social networks, some individuals share their ideas and opinions more frequently than others. These disparities can arise from heterogeneous sociabilities, heterogeneous activity levels, different prevalences to share opinions when engaging in a social-media platform, or something else. To examine the impact of such heterogeneities on opinion dynamics, we generalize the Deffuant–Weisbuch (DW) bounded-confidence model (BCM) of opinion dynamics by incorporating node weights. The node weights allow us to model agents with different probabilities of interacting. Using numerical simulations, we systematically investigate (using a variety of network structures and node-weight distributions) the effects of node weights, which we assign uniformly at random to the nodes. We demonstrate that introducing heterogeneous node weights results in longer convergence times and more opinion fragmentation than in a baseline DW model. One can use the node weights of our BCM to capture a variety of sociological scenarios in which agents have heterogeneous probabilities of interacting with other agents.

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MS34

Characterising Patterns on Real Coloured Spatial Networks Through Random Walks

A large number of interesting phenomena in physics, biology, and social studies result in the formation of large-scale spatial motifs, i.e., non-trivial arrangements of the constituents of the system that cannot be attributed exclusively to randomness. In fact, in many real-world spatial complex systems, including urban environments and biological tissues, the units of the system are often associated with classes or colours. In such structures, the emergence of non-trivial motifs and clusters of regions belonging to the same class are the norm rather than the exception, and the robust quantification of the significance of an observed coloured spatial pattern is a central problem in different fields. In this study, we will present results on two types of real-world datasets: the root cell tissue of different species of plants, and the street network of American cities. In particular, we will quantify the heterogeneity of the coloured patterns associated with real physical quantities on these systems by looking at the Class Mean First Passage Times of random walks over their adjacency graphs. We will show how this diffusion measure can capture not only the macroscopic distribution of patterns, allowing us to make assumptions on the global scale of the systems, but also highlight the heterogeneity in the distribution of colours over the corresponding spatial networks, and permits us to assess the presence of significative correlation in the observed pattern of colours.

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MS34

Spreading and Structural Balance on Signed Networks

Two competing types of node interactions often play an important part in shaping system behaviour, e.g., activatory or inhibitory functions in biological systems. Hence, signed networks, where each connection can be either positive or negative, and the notion of balance, have become popular models and tools recently. Here, we first extend the results in characterising the structure of signed networks to their weighted version in terms of the weighted adjacency matrix, and further show that the contraction of the spectral radius occurs if and only if the network is neither balanced nor antibalanced. These properties are important to understand the dynamics on signed networks, and here we consider two very different ones that are closely related to information propagation: linear dynamics and a version of linear threshold model, both of which have been extended to signed networks. We find consistent patterns of these two theoretically, where the state values can have smaller magnitude than those obtained by ignoring the edge sign only if the network is neither balanced nor antibalanced, subject to appropriate initialisations. We also propose two measures to quantify the distance for a network to be balanced or antibalanced. Finally, we numerically verify these properties through experiments on both synthetic and real networks. The results can also contribute to a better understanding of the problems that are closely related to the dynamics, e.g., the influence maximization.

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MS35

The Large Deviation Principle for W-random Graphs

W-random graph model is a flexible framework for modeling random connectivity, which incorporates many common random graphs including small-world, stochastic block, and power law graphs, to name a few. In this talk, we explain a large deviation principle for W-random graphs and discuss its applications to dynamical networks and to graph signal processing.

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MS35

Continuum Limits of Stochastically Forced Kuramoto Systems

This talk will present recent work on infinite dimensional nonlocal diffusions with additive noise. These may be obtained as the continuum limits of noise driven Kuramoto oscillator systems. A well-posedness theory is developed for this infinite dimensional problem, and convergence results are obtained for both the associated semi-discrete and fully discrete problems. This provides a basis for studying the associated metastability problems of the continuum limit Kuramoto system, which may also be viewed as an approximation of a high, but finite, dimensional problem. Ongoing progress on studying the metastability of exact twisted state solutions, both numerically and analytically will be presented. Novel challenges in the analysis are also highlighted.

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MS35

Propagation of Chaos of Forward-Backward Stochastic Differential Equations with Graphon Interactions

We study graphon mean field games using a system of forward-backward stochastic differential equations. We establish the existence and uniqueness of solutions under two different assumptions and prove the stability with respect to the interacting graphons which are necessary to show propagation of chaos results. As an application of propagation of chaos, we prove the convergence of n-player game Nash equilibrium for a general model, which is new in the theory of graphon mean field games. Based on joint works with Erhan Bayraktar and Xin Zhang.

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MS36

Canards in a Bottleneck

In this talk, we investigate the stationary profiles of a nonlinear Fokker-Planck equation with small diffusion and nonlinear in- and outflow boundary conditions. We consider corridors with a bottleneck whose width has a global nondegenerate minimum in the interior. In the small diffusion limit the profiles are obtained constructively by using methods from geometric singular perturbation theory (GSPT). We identify three main types of profiles corresponding to: (i) high density in the domain and a boundary layer at the entrance, (ii) low density in the domain and a boundary layer at the exit, and (iii) transitions from high density to low density inside the bottleneck with boundary layers at the entrance and exit. Interestingly, solutions of the last type involve canard solutions generated at the narrowest point of the bottleneck. We obtain a detailed bifurcation diagram of these solutions in terms of the in- and outflow rates. The analytic results based on GSPT are further corroborated by computational experiments investigating corridors with bottlenecks of variable width. Joint work with Gaspard Jankowiak, Peter Szmolyan, and Marie-Therese Wolfram

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MS36

The Geometric Blow-Up Method for Pattern Forming Systems

Many authors have demonstrated the utility of the geometric blow-up method as a tool for studying dynamic bifurcations in finite-dimensional slow-fast systems. We focus on the development and application of the geometric blow-up method for PDEs, applied in particular to the scalar Swift-Hohenberg equation with a slow parameter drift on an unbounded domain. In order to understand the dynamics near the dynamic Turing bifurcation which is responsible for the onset of patterned states, we show that the classical multiple scales approximation from modulation theory can be reformulated as a (geometric) blow-up transformation. This leads to an approximating set of non-autonomous Ginzburg-Landau equations, which can be analysed in the blown-up space. Analysing these equations and quantifying the magnitude of the approximation allows for a rigorous description of the solutions in a rich class of weighted Sobolev spaces. We also prove the existence of delayed stability loss phenomena.

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MS36

Geometric Analysis of Fast-Slow PDEs with Fold Singularities

We study a singularly perturbed fast-slow system of two partial differential equations (PDEs) of reaction-diffusion type on a bounded domain. We assume that the reaction terms in the fast variable contain a fold singularity, whereas the slow variable assumes the role of a dynamic bifurcation parameter, thus extending the classical analysis of a fast-slow dynamic fold bifurcation to an infinite-dimensional setting. Our approach combines a spectral Galerkin discretisation with techniques from Geometric Singular Perturbation Theory (GSPT) which are applied to the resulting high- dimensional systems of ordinary differential equations (ODEs). In particular, we show the existence of invariant manifolds away from the fold singularity, while the dynamics in a neighbourhood of the singularity is described by geometric desingularisation, via the blowup technique. Finally, we relate the Galerkin manifolds that are obtained after the discretisation to the invariant manifolds which exist in the phase space of the original system of PDEs.

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MS37

Forecasting Cardiac Dynamics Using Reservoir Computing: Effect of Training Data Length on Prediction Length and Quality

The heart can exhibit complex and potentially chaotic electrical dynamics. Time-series forecasting of such dynamics could enable new methods of intervention and control. Recent reservoir-computing-based work in this area has shown accurate predictions of multiple future action potentials, but it is unknown how the predictive abilities of this approach vary with different lengths of training data. In this talk, we discuss our investigation into this question and show how the prediction horizon of this forecasting method depends on the length of data used during training. In addition, we examine how this relationship changes for more complex dynamics, including alternans and recordings from tissue with complex spiral wave breakup.

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MS37

Speeding up Cardiac Simulations with Parallel-in-Time Methods

Numerical integration of cardiac electrical models and the complex spatiotemporal dynamics they display is well-suited to parallelization over the spatial component of the problem domain. Modern computer hardware, such as GPUs, may not be fully utilized without an extremely fine-grained spatial discretization. Parallel-in-time (PinT) integration presents a promising opportunity to further speed up the numerical solution of partial differential equations. However, the accuracy and efficiency of these methods depends on the properties of the specific PDE in question. While both heat and wave equations have been studied as model PDEs for PinT methods, less attention has been placed on excitable systems. In this talk, I will present my work on adapting PinT methods to cardiac models, with a focus on the practicality of using these methods considering accuracy, speedup, and ease of implementation.

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MS37

WebGL Implementation of Spatially Heterogeneous Cardiac Models

Cardiac disease has remained as one of the leading causes of death in US and globally. Computer aided modeling has proven to be a vital tool to offer mechanistic insights to the initiation and termination of arrhythmias. However, numerical simulation of cardiac tissue using cell models is computationally demanding and traditionally has been achieved using super computers. GPU computing has been suggested as an alternative in recent years to offer tissue modeling on personal computers. Specifically, WebGL has been proposed as a cross platform GPU implementation that is portable and freely available on all modern browsers. A wide variety of arrhythmias are dynamic phenomena that emerge at the tissue level and variability in cardiac cell models leads to significant changes in the cells dynamic response. If this variability is introduced spatially in the tissue it can lead to spatial emergent phenomena. In this study, we focus on how spatial heterogeneity at the cardiac cell models can be implemented using WebGL 2.0. Then, we will present the arrhythmogenic effects that the spatial heterogeneity can have in the cardiac system

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MS37

Impact of Voltage- and Calcium-Driven Alternans on Observability of a Cardiac Ionic Cell Model

Lethal arrhythmias are sometimes preceded by electrical alternans, which is a beat-to-beat alternation in cardiac action potential duration. A current technological obstacle is that many variables, such as ionic concentrations and gating states, contribute to arrhythmia formation but cannot be measured directly and simultaneously in a lab setting. One solution is to develop data assimilation algorithms, which combine available data with predictions from a dynamical model to reconstruct unmeasured quantities. To learn more about prospects for data assimilation, we performed an observability analysis on the Shiferaw-Sato-Karma (SSK) model of a cardiac myocyte. Observability is a model property that indicates whether all dynamical variables can be reconstructed from a proposed measured quantity. We numerically linearized the SSK model and assessed observability of its largest modes over a range of simulated measurements, where each type of measurement consisted of recording a single variable periodically. We found that the strategies that yielded strongest observability were to measure the slow I_{Na} inactivation gate during voltage-driven alternans and the submembrane calcium concentration during calcium-driven alternans. Although various strategies, such as inferring the state from membrane potential, were found to be viable for either mechanism, our results indicate that alternans mechanisms can affect which types of measurements are most informative.

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MS38

Disease Case Introductions

I will discuss work on disease case introductions, i.e., the process through which new disease cases are introduced into a jurisdiction. Case introductions play a fundamental role during the early phase of propagation: if the disease is absent from a location, then it is through introductions that they are introduced there. However, their importance quickly fades as locally initiated transmission chains take over. To model the different phases and understand the drivers of introduction and spread, I consider several stochastic models and make use of a so-called "importation layer", which allows quantifying the contributions of introduced and locally generated cases to the overall spread in a location.

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MS38

Multiscale Modelling of Immunity

Immunity is gained from infection and vaccination, but effective immunity can also wane over time, with antibody and/or memory cell decay in the body, and with the evolution of a pathogen to more fit strains/variants. We have developed mathematical models of infection and immunity at the in-host and population levels. At the in-host level, we track the interaction of the immune system with a pathogen or vaccine proteins to quantify the generation of antibodies and memory cells in the body. We also estimate the probability of individual infection given particular immunity characteristics and pathogen immune escape mechanisms at the time of pathogen exposure. Results from the in-host models are used to inform immunity and infection severity dynamics in population-level models of pathogen spread and public health vaccination programs. In this talk, we will review in-host models of vaccination and infection, and we will provide an overview of infection and immunity incorporation into mathematical epidemiological models of disease spread and vaccination programs. Particular attention will be made to estimation of population seroprevelance with application to COVID-19.

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MS38

Integrating Genomic and Epidemiologic Data to Identify Who-Infected-Whom in Two Healthcare Facilities

More than 2.8 million people acquire antibiotic-resistant infections and 223,000 people are hospitalized with Clostridioides difficile annually. Antibiotic resistant bacteria are particularly deadly in healthcare facilities (HCF) as they disproportionality impact the most vulnerable populations. Our ability to control the spread of pathogens in HCFs is limited by our incomplete understanding of how they spread. Since patients rarely directly contact each other, it is assumed that most transmission occurs through an intermediary vector. Alas, many challenges remain in identifying these vectors including the near infinite number of potential transmission routes; that many pathogens are detectable and robust in the HCF environment, obscuring transmission routes; and since bacteria can colonize without causing infection, it is difficult to separate introductions from transmissions without comprehensive surveillance. The widespread availability of genomic data and increase in computing power has resulted in a rapid development of methods that have significantly improved our ability to reconstruct transmission trees for viruses. However, methods for bacteria have not kept pace. Using densely sampled genomic data from patients, healthcare workers (HCW), the environment, and data on HCW movement, we extend existing methods to create a generalizable method to reconstruct transmission trees to better understand how pathogens are spreading within HCFs and improve control strategies.

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MS38

Modeling the Spread of Dengue Virus: the Importance of Appropriate Spatial Scales

Dengue virus is the most significant viral mosquito-borne infection in terms of its human impact. Mathematical modeling has contributed to our understanding of its transmission and control strategies aimed at halting its spread. We consider the spread of dengue at the level of a city. Because the *Aedes aegypti* mosquito that transmits dengue has relatively low dispersal over its lifetime, human movement plays a major role in its spread and the household is a key spatial scale on which transmission occurs. Simple multi-patch deterministic models—metapopulation models, which consider the population to be described as a network of well-mixed patches—have been used to model city-level spatial spread and can provide expressions for key epidemiological quantities such as the basic reproduction number, R_0. We compare dynamics predicted by such models with results from individual-based network models and illustrate several discrepancies. We argue that the small size of households and local depletion of susceptibles are key features of the dynamics that are not captured in the standard R_0 analysis of the ODE model. In order to gain analytic understanding, we propose the use of household-level models, which can be analyzed using branching process theory. Our work, which echoes results previously found for directly-transmitted infections, highlights the importance of correctly accounting for the relevant spatial scales on which transmission occurs

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MS39

Modeling Thresholds for Post-Rebound Control of SHIV Using AAV-Vectors Encoding eCD4Ig

The human immunodeficiency virus (HIV) is a retrovirus infecting primarily CD4 T cells. Antiretroviral therapy (ART) suppresses the observed plasma HIV viral load below the detection limit. Although successful in controlling virus replication, ART is not a cure for HIV and must be taken for life. One gene-based approach for HIV cure is Adeno-associated virus (AAV) vectors encoding the antibody-like peptide eCD4Ig that neutralizes most HIV variants. Ongoing pilot studies examine if AAV-delivered eCD4Ig can induce post-rebound control in Simian-HIV (SHIV)-infected primates after ART interruption. However, the number of animals, cost, and time to perform these experiments make it difficult to find the optimal conditions to produce post-rebound control. We apply mathematical models to find ways to use this novel therapeutic approach that cannot be explored experimentally. We adapt standard within-host models of virus dynamics to fit viral load data from SHIV-infected rhesus macaques during acute infection, ART, and ART interruption with and without eCD4Ig-expressing AAV inoculation. We model the mechanisms behind AAV-vector infection kinetics and eCD4Ig production and fit the models to serum rh-eCD4Ig in SHIV-infected and healthy animals. Using the data-validated model, we seek to use simulated experiments to find: 1) optimal doses of AAV-encoding eCD4Ig, 2) optimal schedules of AAV administration, and 3) optimal times of ART interruption to ensure post-rebound control of SHIV.

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MS39

Mathematical Modeling of Hiv-1 Dynamics Suggests That VRC07-523-LS Has High Neutralization Potency and Mediates ADCC In-Vivo

VRC01, VRC01LS and VRC07-523LS are broadly neutralizing antibodies (bnAbs) that target the CD4 binding site of gp120 on the HIV-1 envelope. VRC01LS and VRC07-523LS are enhanced modifications of the VRC01 and VRC07 antibodies. Phase 1 clinical trials have been performed by the NIH to assess these bnAbs safety and effect on viremia in HIV-chronically infected individuals off antiretroviral therapy (ART). After an infusion of a bnAb, most participants had a viral decline of more than 1-log10 followed by a rebound. Here, we fit mathematical models of pharmacokinetics and virus dynamics to serum bnAb concentrations and plasma viral loads from each participant. We assumed two pre-existent viral populations, one sensitive to a given bnAb and one resistant. Our modeling showed that the half-life of VRC01LS and VRC07-523LS was up to four times that of VRC01, but with VRC01LS final concentration higher than VRC07-523-LS. We used an in vivo half maximal inhibitory coefficient (IC_{50}) estimated from the model as an indicator of the bnAbs relative potency and found that VRC07-523LS is the most effective at neutralization. We also found a higher infected cell death rate for those receiving VRC07-523-LS compared to the other bnAbs or ART, suggesting a Fc-mediated effect. In conclusion, our model recapitulates the antibody and virus dynamics from individuals receiving a bnAb and found VRC07-523LS to have the highest in vivo neutralization potency with a possible Fc-mediated effect.

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MS39

Modeling the Viral Resistance to Monoclonal Antibody Treatment for Sars-CoV-2

The COVID-19 pandemic has led to approximately 630 million cases and 6.6 million deaths. To mitigate the loss of lives, emergency authorization was given to several monoclonal antibody therapies for the treatments of mild-to-moderate SARS-CoV-2 patients with high risks of progressing to severe disease. Neutralizing monoclonal antibody treatments target the viruss spike proteins to block its ability to enter and infect target cells. Monoclonal antibody therapy can thus accelerate the decline in viral load, which results in a lower hospitalization rate among high-risk patients. However, viral resistance can emerge and lead to the occurrence of transient viral rebound of 3-4 logs in some patients treated with monoclonal antibody therapy. This raises an urgent concern regarding drug resistance that could compromise the efficacy of monoclonal antibody therapy. In this study, we develop mathematical models and fit them to data from SARS-CoV-2 patients treated with one such monoclonal antibody, namely Bamlanivimab. Our results demonstrate that a mechanism, which allows virus access to additional supply of target cells during the infection, is necessary to describe the emergence of resistant virus associated with viral rebound of 3-4 logs.

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MS39

Modeling Immunotherapy for Hiv

Immunotherapy for HIV can take many forms. One important modality involves the administration of one or more broadly neutralizing antibodies (bnAbs) directed HIV. A recent phase 1 clinical trial evaluated the safety, pharmacokinetics and antiviral efficacy of the HIV-1 V3-glycan-specific antibody PGT-121. Following a single infusion of PGT-121 at a dose of 30 mg/kg, plasma viral load decays were reported in 10 study participants. In 8 out these 10 of the responders, viral rebound occurred by 28 days post-treatment with the rebound virus demonstrating resistance to PGT-121 in in vitro neutralization assays. The remaining two participants exhibited ART-free viral control for over 168 days. ART-free remission for ¿ 168 days had not previously been reported after a single dose of one or multiple bnAbs. Here, I will show how a mathematical model allows one to understand the interplay between antibody potency and time to viral rebound as well as the mechanisms underlying the evolution of resistance to PGT-121. I will also briefly discuss a novel immunotherapy experiment in ART suppressed rhesus macaques in which durable viral remission was obtained in most of the animals given a combination of the IL-15 superagonist N-803 and broadly neutralizing antibody therapy. Here a viral dynamic model to be presented incorporating an effector cell response as well as exhausted effector cells was used to analyze the viral rebound kinetics and durable control.

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MS40

Invariant Tori in Periodic and Quasi-Periodic Hamiltonian Systems

In this talk we overview several algorithms to compute and validate invariant tori in periodic and quasi-periodic Hamiltonian systems. The proof of convergence of the algorithms leads to a posteriori format KAM theorems. The algorithms lead also to efficient computer programs.

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MS40

Fully Numerical Computation of Heteroclinic Connection Families in the Spatial Three-Body Problem

Heteroclinic connections play an important role in astrodynamics, enabling fuel-efficient spacecraft transfers and a mechanism to understand transport phenomena in our solar system. The circular restricted three-body problem (CR3BP) offers a simple model of spacecraft dynamics in which these solutions can be studied. At a given energy level in the spatial CR3BP, two-parameter heteroclinic connection families exist between three-dimensional normally hyperbolic invariant manifolds (NHIM) foliated by two-dimensional hyperbolic tori. In this talk, we will present a methodology for computing these families. The computation of connections can be formulated as a two-point boundary value problem (TPBVP) in which the end points of the trajectory belong to the unstable and stable tangent bundles of invariant tori populating a pair of NHIMs. In previous studies, the boundary conditions required to solve the TPBVP have been obtained by leveraging semi-analytical expansions of the dynamics around fixed points. Under our approach, they are achieved by modifying an existing flow map method, a fully numerical approach to torus computation. Utilizing fully numerical techniques allows us to consider connections between orbits outside semi-analytical approaches' domain of validity. We will demonstrate the methodology by computing families of connections from tori around Earth-Moon L1 to tori around Earth-Moon L2.

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MS40

Flow Map Parameterization Methods for the Computation of Invariant Tori in Celestial Mechanics Models

The goal of this talk is to present a methodology for the computation of lower-dimensional (non-Lagrangian), partially hyperbolic invariant tori of autonomous Hamiltonian systems. It is therefore well suited (but not limited to) models from Celestial Mechanics such as the circular, spatial RTBP, spatial Hill or the gravity field around a uniformly rotating, irregular body. It combines flow map (a.k.a. stroboscopic map) methods, parameterization methods and symplectic geometry. While flow map methods reduce the dimension of the tori to be computed by one, parameterization methods make the computational cost negligible with respect to (the unavoidable) numerical integration. Symplectic geometry is responsible for some cancellations that make the cohomological equations solvable. The method simultaneously computes the tori and their invariant stable and unstable bundles. An application is made to the computation of the Lissajous family of tori around L_1 in the Earth-Moon circular, spatial RTBP. In this application, when compared to more classical ("large-matrix") discretization techniques of the invariance equations, the speedup factor of the method is > 10.

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MS40

Invariant Manifolds Around Earth-Moon L1 and L2 in the Hill Restricted Four-Body Problem

The Hill Restricted Four-Body Problem (HR4BP) is a time periodic Hamiltonian dynamical system that generalizes the Restricted Three-Body Problem (R3BP) in a coherent way [D. Scheeres, The Restricted Hill Four-Body Problem with Applications to the Earth-Moon-Sun system]. This work focuses on the dynamics near the Earth-Moon L_1 and L_2 dynamical substitutes in the HR4BP, drawing comparisons to similar studies in the Bicircular and Quasi-Bicircular Problems (BCP, QBCP) by Rosales and Jorba [J.J. Rosales, On the effect of the Sun's gravity around the Earth-Moon L_1 and L_2 libration points]. By means of a periodic time-dependent reduction to the center manifold, we show the existence of families of 2- and 3-dimensional quasi-periodic invariant tori around L_1 and L_2. The reduction to center manifold procedure is a normal form technique which exploits Lie transforms to construct an approximate formal first integral, the saddle integral, which is set equal to zero in order to study the dynamics on the center manifold; however, one can use the saddle integral to generate stable/unstable manifold coordinates to a high-order approximation. Hence, the reduction to center manifold procedure is also used to approximate the center-stable/unstable manifolds in the cis- and translunar regions. These hyperbolic invariant manifolds open the possibility of homo- and heteroclinic connections to/from the cis- and translunar regions.

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MS41

Shifting Parties in Social Dynamics – A Nonlocal Approach

The bounded confidence model is well-known for its dynamics of party formation within the sphere of social dynamics. We investigate the addition of bias terms, modeling shifts in opinions, and the resulting dynamics including coherent movement of parties. We analyze this coherent movement using a novel, nonlocal approach for the study of the resulting forward-backward delay equations. Different from existing methods, we compute Taylor expansions in function space. This approach leads to an algebraically simple computation of the reduced flow on the center manifold, allowing for proof of coherent small-amplitude movement.

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MS41

Macroscopic Wave Propagation for Lattices with Random Material Coefficients

In the paper [A. Mielke, *Macroscopic Behavior of Microscopic Oscillations in Harmonic Lattices via Wigner-Husimi Transforms.*, Arch. Rational Mech. Anal. 181 (2006)], the approximation of solutions to harmonic lattices by macroscopic waves is rigorously justified for Bravais lattices of any dimension with periodically varying material coefficients. In this talk, we explore the effects of having random coefficients in such lattices. Specifically, the talk will discuss the approximation of solutions to the lattice differential equation $m\ddot{u} = \Delta u$ with macroscopic initial data by an effective wave equation. Here, m (the masses) are random variables that are contained in some positive interval, and Δ is the Laplace operator for the d-dimensional integer lattice. "Macroscopic initial data" refers to the fact that the initial conditions are scaled by a small parameter ϵ i.e. $u_0(x) = \epsilon^{-1}\phi(\epsilon x)$ and $\dot{u}_0(x) = \psi(\epsilon x)$ where $x \in \mathbb{Z}^d$. The talk will focus on the role of the random masses in the approximation and how the dimension of the lattice becomes important when the masses are random.

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MS41

The Monoatomic Fpu System As a Limit of a Diatomic FPU System

I review results on a diatomic infinite FermiPastaUlam (FPU) system with light and heavy particles. For a small mass ratio, we prove error estimates for the approximation of the dynamics of this system by the dynamics of the monoatomic FPU system. The light particles are squeezed by the heavy particles at the average value of their displacements. The error estimates are derived by means of the energy method and hold for sufficiently long times, for which the dynamics of the monoatomic FPU system is observed. The approximation result is restricted to sufficiently small displacements of the heavy particles relatively to each other. Based on this asymptotic reduction, I will describe new results on existence of traveling solitary waves at the discrete set of their velocities.

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MS41

Stochastic Soliton Dynamics in the Korteweg-De Vries Equation with Multiplicative Noise

In recent years, stochastic traveling waves have become a major area of interest in the field of stochastic PDEs. We study the behavior of solitons in the Korteweg-de Vries equation under the influence of multiplicative noise. We introduce stochastic processes that track the shape and position of solitons over long time-scales based on a frozen-frame formulation and stability properties of the linearized frozen-frame evolution. We formulate leading-order approximations for the stochastic soliton amplitude and position, and compare their dynamics with numerical simulations.

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MS42

Dirac Synchronization: Explosive Transition and Emergent Rhythmic Phase

Topology, key to capture higher-order network dynamics, provides the mathematical tools to treat topological signals i.e. dynamical variables defined on nodes, links and higher-order simplices in a simplicial complexes. Topological signals of a given dimension explosively synchronize under global and adaptive coupling (Millan et al. 2020, Phys. Rev. Lett. 124:218301). With Dirac synchronization (Calmon et al. 2022, Commun. Phys. 5:253; Calmon & Bianconi 2022, arXiv:2210.16124), we introduce a mathematical framework that uses the Dirac operator (Bianconi 2021, J. Phys. Complexity 2:035022) to couple locally and topologically oscillating phases associated to simplices of different orders. Both our extensive numerical and theoretical results reveal that Dirac synchronization on fully connected networks and on sparse uncorrelated networks is explosive. The phase diagram indeed contains a discontinuous forward phase transition. The backward transition however can be either continuous or discontinuous depending on the tuneable amplitude of the phase lag, and the resulting hysteresis loop is thermodynamically stable. One of the fascinating features of Dirac synchronization is that its synchronized phase is non-stationary, and the complex order parameter coherently oscillates at an emergent non-zero frequency. This exotic rhythmic phase could shed light on topological mechanisms for the emergence of brain rhythms.

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MS42

Criticality on Networks: Universality Classes, Power Laws, and Dragon Kings

The term criticality usually refers to a system in the midst of a thermodynamic phase transition. Second-order phase transitions, which are characterized by correlations lengths and response functions that display power-law divergences, occur broadly in physical systems such as the percolation transition of connectivity on lattices and networks. Instead of a thermodynamic transition, a dynamical system can display "self-organized criticality" (SOC) where the interplay of competing objectives drives the system to an asymptotic state showing power law distributions of event sizes. Both the theory of second-order phase transitions and SOC guide our understanding of criticality in real-world systems. Yet, missing from those theories is that real-world systems often have self-amplifying mechanisms that kick-in once a system reaches a tipping-point causing massive events referred to as "Dragon Kings", for instance bubbles in financial markets or massive failures in infrastructure. Here we first discuss percolation on networks and the strong impact that small interventions to enhance or delay the onset of the percolation transition can have on its critical behavior. Then we discuss how SOC can lead to the emergence of Dragon Kings using models motivated by engineered systems and by cascading failures in networks of oscillators.

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MS42

Bounded-Confidence Models of Opinion Dynamics on Networks

Mathematical models of opinion dynamics examine how opinions of entities in a network change through their interactions with each other. One well-known type of opinion model are bounded-confidence models (BCMs), in which entities have continuous-valued opinions. The opinions of two or more entities compromise through interactions as long as the opinions are sufficiently close to each other. In this talk, I will discuss consensus, polarized, and fragmented (i.e., three or more opinion clusters) steady states in BCMs. I will examine transitions between these qualitatively different steady states (which depend on how close opinions need to be for compromises to occur) in BCMs with a variety of features, including polyadic interactions, smoothed-out opinion-update rules, and network adaptivity.

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MS42

Generic Criteria for Abrupt Synchronization Transitions: Exploring Subcriticality and Folds in Coupled Oscillator Systems

The properties of phase transitions and bifurcations in macroscopic system dynamics remains central in the study of network-coupled dynamical systems. In particular, the presence of subcriticality, folds, and other nonlinear properties in bifurcation structures inform important properties in the state dynamics, for instance the presence of multistability and abrupt transitions between different states. In this talk we will study the transitions and bifurcations between macroscopic states in large systems of coupled phase oscillators. We will begin with a classical formulation of Kuramoto oscillators and explore the onset of synchronization, ultimately deriving a generic condition for the emergence an explosive, i.e., abrupt, transition between incoherence and synchronization via a subcriticality. Next, we explore the coupled oscillator systems with time-delayed higher-order interactions. While both time delays and higher-order interactions have been shown to induce sub criticality in the onset of synchronization on their own, we show here that their combination leads to additional folds that induce multistability and abrupt transitions via the formation of a double saddle-node bifurcation rather than subcriticality.

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MS45

Challenges in Hybrid Modelling of Nonlinear Dynamical Systems

In this introductory talk to this minisymposium, I will reflect on the challenges in hybrid modelling of dynamical systems, and present our results on including measurement data with machine-learnt structures inside differential equations alongside algebraic terms representing mechanistic models. By having a physics-based core, the so-called universal differential equation (UDE) models can incorporate the insight and expertise one has on the behaviour of the modelled structure. However, every physics-based model involves some degree of error compared to measurement data due to the dynamics neglected by the model. Most of the studies on UDEs however focus on identifying a well-fitting model with a constant set of system parameters while it is often also interesting to investigate the system's response to varying parameters, e.g., to allow for parameter-uncertainty, or to incorporate the change of external conditions. This study focuses on nonlinear dynamical systems and learning measured bifurcation diagrams using the UDE models leading to inherently varying-parameter problems. The results indicate that that this modelling approach has a great potential in delivering accurate models of nonlinear dynamical systems whereas I will also report on the challenges encountered during the training procedure, such as overfitting and finding local minima of the objective function and discuss the potential ways of avoiding these issues.

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MS45

Discrepancy Modeling For Experimental Data

Physics-based and first-principles models pervade the engineering and physical sciences, allowing for the ability to model the dynamics of complex systems with a prescribed accuracy. By focusing explicitly on the discrepancy between measured and modeled dynamics, our framework shifts the view of discrepancies as errors or residuals to highly valuable measures for model improvement and scientific insight. We discuss two nuanced, yet distinct, discrepancy modeling approaches and demonstrate how different data-driven methods can be used interchangeably within this framework. Further, we emphasize discrepancy modeling considerations and trade-offs related to model interpretability and sensor constraints. We highlight a few applications in which discrepancy modeling provides insight into what we know and what we may be missing.

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MS45

Combining Data Assimilation and Neural ODEs for Learning Hybrid Models of Dynamics

The development of data-informed predictive models for dynamical systems is of widespread interest in many disciplines. Here, we present a unifying framework for blending mechanistic and machine-learning approaches for identifying dynamical systems from data. This framework is agnostic to the chosen machine learning model parameterization, and casts the problem in both continuous- and discrete-time. We will focus on recent developments that fuse data assimilation with auto-differentiable ODE solvers which, when combined, allow us to learn from noisy, partial observations. We will also present comments on reservoir computers and their connections to random feature (and hence, kernel) methods.

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MS46

The mpEDMD Algorithm: Structure-Preserving and Convergent Koopmanism

Koopman operators globally linearize nonlinear dynamical systems, and their spectral information can be a powerful tool for the analysis and decomposition of nonlinear dynamical systems. However, Koopman operators are infinite-dimensional, and computing their spectral information is a considerable challenge. We introduce measure-preserving extended dynamic mode decomposition (mpEDMD), the first Galerkin method whose eigendecomposition converges to the spectral quantities of Koopman operators for general measure-preserving dynamical systems. mpEDMD is a data-driven and structure-preserving algorithm based on an orthogonal Procrustes problem that enforces measure-preserving truncations of Koopman operators using a general dictionary of observables. It is flexible and easy to use with any pre-existing DMD-type method and with different data types. We prove the convergence of mpEDMD for projection-valued and scalar-valued spectral measures, spectra, and Koopman mode decompositions. For the case of delay embedding (Krylov subspaces), our results include convergence rates of the approximation of spectral measures as the size of the dictionary increases. We demonstrate mpEDMD on a range of challenging examples, its increased robustness to noise compared with other DMD-type methods, and its ability to capture the energy conservation and cascade of a turbulent boundary layer flow with Reynolds number ¿ 60000 and state-space dimension ¿100000.

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MS46

Numerical Aspects and Software Tools for the Koopman Framework for Computational Data Driven Analysis of Dynamical Systems

The Dynamic Mode Decomposition (DMD) is a method for computational analysis of nonlinear dynamical systems in data driven scenarios. Based on high fidelity numerical simulations or experimental data, the DMD can be used to reveal latent structures in the dynamics or as a forecasting or a model order reduction tool. The theoretical underpinning of the DMD is the Koopman composition operator on a Hilbert space of observables of the dynamics under study. The numerical realization of the method is in the framework of numerical linear algebra. This talk presents a LAPACK implementation of a variant of the DMD, based on the state of the art numerical linear algebra. Fine numerical issues of error analysis and perturbation theory are discussed in detail. For instance, the method returns residuals for all computed Ritz pairs, so that, even in a data driven setting, one can select good approximate eigenpairs. Further, a compression scheme, based on the QR factorization, allows for a more efficient computation and fast updating in cases of high dimensional streaming data. As a particular case study example, we consider data snapshots generated by Hermitian matrices and show how to mitigate numerical difficulties and preserve hermiticity and guarentee real spectrum and orthonormal eigenvectors. Finally, we discuss the case when the underlying operator is highly non-normal.

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MS46

Koopman Reduced Order Modeling with Confidence Bounds

This talk introduces a reduced order modeling technique based on Koopman operator theory that gives confidence bounds on the model's predictions. It is based on a data-driven spectral decomposition of said operator. The reduced order model is constructed using a finite number of Koopman eigenvalues and modes while the rest of spectrum is treated as a noise process. This noise process is used to extract the confidence bounds. Additionally, we propose a heuristic algorithm to choose the number of deterministic modes to keep in the model. We assume Gaussian observational noise in our models. As the number of modes used for the reduced order model increases, we approach a deterministic plus Gaussian noise model. The Gaussianity of the noise can be measured via a Shapiro-Wilk test. As the number of modes increase, the modal noise better approximates a Gaussian distribution. As the number of modes increases past the threshold, the standard deviation of the modal distribution decreases rapidly. This allows us to propose a heuristic algorithm for choosing the number of deterministic modes to keep for the model.

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MS46

Finite Difference Approximations for Sindy on Stochastic Systems

Given data from a nonlinear dynamical system, the Sparse Identification of Nonlinear Dynamics (SINDy) framework was developed to identify nonlinear systems and present them as an interpretable differential equation,

$$\dot{x} = f(x).$$

It does this by using a dictionary of functions and representing f as a sparse linear combination of these dictionary functions. These methods have also been extended the stochastic differential equation,

$$dX_t = \mu(X_t)dt + \sigma(X_t)dW_t,$$

governing Ito drift-diffusion processes, where the SINDy algorithm can be used to estimate the drift function, μ, and the square of the diffusion matrix, σ^2. However, using the simple, first order estimates for μ and σ^2 requires large amounts of data sampled at a very high frequency to obtain accurate results. We present how we can use alternate methods to approximate μ and σ^2 for use in the SINDy algorithm to obtain higher orders of accuracy. Further, for each of the methods presented, we demonstrate the convergence rates of the algorithm both with respect to the sampling frequency and the length of the trajectory for which data is available. Testing the various methods on nonlinear SDEs shows significant improvements on the accuracy of the estimates. This allows us to estimate the parameters of the SDE using far less data.

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MS47

Fredholm Determinants, Evans Functions and Maslov Indices for Partial Differential Equations

The Evans function is a well known tool for locating spectra of non-self-adjoint differential operators in one spatial dimension widely used to detect stability and instability of traveling and standing waves. A major unsolved problem in many spatial dimensions is to construct its analogue, that is, a function whose zeros and poles would correspond to the eigenvalues of the respective PDE operators. In this work joint with G. Cox and A. Sukhtayev we construct a *multidimensional* analogue of the Evans function as the modified Fredholm determinant of a ratio of Dirichlet-to-Robin operators on the boundary. This gives a tool for studying the eigenvalue counting functions of second-order elliptic operators that need not be self-adjoint. We discuss relations between the spectra of the non-self-adjoint elliptic multidimensional differential operators and nonlinear Robin-to-Robin, Robin-to-Dirichlet, and Dirichlet-to-Robin operator pencils. In the self-adjoint case we relate our construction to the Maslov index, another well known tool in the spectral theory of differential operators. This gives new insight into connections between the Evans function and the Maslov index, allowing us to obtain crucial monotonicity results for the Maslov index.

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MS47

More Traveling Waves in the Holling-Tanner Model with Weak Diffusion

We identify two new traveling waves of the Holling-Tanner model with weak diffusion. One connects two constant states; at one of them, the model is undefined. The other connects a constant state to a periodic wave train. We exploit the multi-scale structure of the Holling-Tanner model in the weak diffusion limit. Our analysis uses geometric singular perturbation theory, compactification and the blow-up method.

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MS47

Bounded C0-Semigroups and Applications to Linear Stability of Heteroclinic Solutions in Precipitation Models

We prove the linear stability of heteroclinic solutions of certain classes of models arising in chemical dynamics. Our method relies on finding necessary conditions that guarantee the boundedness of a semigroup of operators on a Hilbert space whose generator can be decomposed as a product of self-adjoint operators. This result is applied to the case of a linearization along the wave that has a block-matrix decomposition.

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MS47

Eigenvalues Without Determinants: from Evans Functions to Spreading Speeds

I'll present novel numerical tools that avoid Wronskians and determinants when determining stability and instability in unbounded domains. Rather than finding roots of determinants, the algorithms consider the pointwise intersection problem of stable and unstable subspaces as a nonlinear (in the spectral parameter) eigenvalue problem. Inverse power methods for this nonlinear eigenvalue problem lead to infinite-delay recursions, which can be understood theoretically and effectively implemented computationally. I'll mention applications towards the computation of spreading speeds for fronts and towards the computation of resonances in Schroedinger operators with higher-order dispersion.

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MS48

Reduced Models from Data: a Selective Overview of Issues and Approaches

Reduced models of complex nonlinear dynamic phenomena are of interest for many reasons: they reduce computational cost, offer insights into mechanisms, and enable deeper analysis. Recent computing advances have rejuvenated the field, both because the data-driven methods they enable are especially useful in problem domains where first-principles models are impractical or unavailable, and because reduced models are increasinlyg used to make sense of large datasets. In this overview, I will highlight some of the many issues that arise in model reduction and data-driven modeling and touch on some useful conceptual frameworks and dynamical ideas, focusing in particular on those relevant to the talks in this minisymposium.

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MS48

Learning Climatological Wind Data with Implicit Neural Representations

Wind energy is a leading renewable energy source. It does not pollute the environment and reduces greenhouse gas emissions that contribute to global warming. However, current wind characterization is performed at a resolution insufficient for assessing renewable energy resources in different climate scenarios. In this paper, we advocate the use of deep learning methods to learn generative models of wind fields. In contrast to existing approaches, we formulate the generative model as a function of the spatial coordinate, thereby learning a highly-accurate continuous representation of the wind field from discretized data. We extend the concept of conditional parameterization by generating the parameters of the proposed model by encoding the discretized low-resolution wind data. Such resolution enhancement may enable essential localized analyses of renewable energy resources' long-term economic sustainability.

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MS48

Data-Driven Reduced-Order Modeling of Lagrangian Turbulence

Fully resolving turbulent flows in physical sciences and engineering applications using Direct Numerical Simulation (DNS) is in general prohibitively expensive due to the existence of a wide range of scales, non-linearity, and chaos. This challenge has motivated the development of efficient reduced-order models of turbulence dynamics, which has gotten a remarkable new boost from disparate fields of Physics-informed Machine Learning (PIML). The talk represents an overview of our efforts in developing reduced-order models describing various aspects of Lagrangian turbulent dynamics under the PIML paradigm. We inject physical constraints into the construction of Neural Network models for turbulence dynamics at both coarse-grained scale (Lagrangian Large Eddy Simulation) and Kolmogorov scale (based on Velocity Gradient Tensor dynamics). A large Lagrangian dataset is extracted from high-Reynolds number DNS and used to train the PIML models. Through a series of diagnostic tests, we show that the trained models are capable of producing the correct flow structures and turbulence statistics in homogeneous isotropic turbulence.

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MS49

Mean-Field Reduction for Random Systems Heterogeneously Coupled on Complex Networks

Consider a complex network on N nodes; on each node sits a random dynamical system, and node systems interact pairwise if there is an edge connecting the pair of nodes. This gives rise to an N-dimensional system with emergent behaviour due to interactions. The hubs, i.e., very well-connected nodes, experience a non-negligible and predictable net effect from the interactions; this predictable emergent behaviour is referred to as its mean-field reduction. We present abstract results for such reduction on a general class of networks and for a general class of node dynamics, as well as some concrete examples. This is joint work with Tiago Pereira and Jeroen Lamb.

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MS49

Chaotic Transitions in Hamiltonian Coupled Pendula

We study a class of Hamiltonian systems consisting of pendula coupled by an interaction 'potential entailing strong symmetric and geometric structure. Such networked systems show a rich behaviour, ranging from periodic motion to unbounded trajectories passing trough chaos. Thanks to the properties of the coupling, we are able to obtain several analytical results concerning the systems under analysis. We show the different dynamical scenarios by using simulations, characterising the chaotic regime by classical methods, such as Poincar maps and Lyapunov exponents. Furthermore, we conjecture the existence of a phase transition regulated by the energy of the system and the geometrical nature of the appearance of chaos.

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MS49

Contact Processes on Simplicial Complexes

When it comes to interacting particle systems (IPS) on graphs, the underlying idea is to associate to each node a state and define a dynamical system on the graph by specifying the interaction between vertices along the edges. For our purpose, we study IPS through the example of contact processes on more general geometric structures given by simplicial complexes. The classical contact process on the integer lattice is defined by two update rules, the recovery of an infected vertex at a given rate and the infection of a susceptible vertex at a rate proportional to the number of infected neighbours. On top, we will not only consider binary interactions of two vertices along an edge but interaction across higher dimensional simplices. We will study the mathematical basis of the process (in terms of markov processes), the existence of invariant measures, and the related influence of the simplicial structure on dynamics. We will define k-spin systems by modifying the update rules, prove existence as Feller process and develop lower and upper bounds for the critical values that mark the transition from extinction to survival (for lattice-like simplicial complexes also known as epidemic threshold). On the macroscopic level, we consider the Gillespie algorithm for k-spin systems and develop a master and mean-field equation for particular models.

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MS49

Canard Cascading in Systems with Slow-Fast Coupling

We describe the mechanism behind the phenomenon of canard cascading observed in a model of globally coupled semiconductor lasers. The coupling in the system is realized by a slow variable, and consequently the slow-fast properties of the system lead to the appearance of multiple branches of slow manifolds. The canard cascading orbits are solutions that switch between these branches. Such switching can be periodic and lead to multiple unstable branches being visited. These types of solutions can form robust limit cycles.

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MS50

Function Space Methods for the Analysis of Infinite-Dimensional Fast-Slow Systems

Neural field equations (NFEs) have become an important tool in mathematical neuroscience to model dynamical behavior in the brain on macroscopic scales. They can be thought of as spatially continuous extensions of large-scale neuronal networks and can therefore be interpreted as infinite-dimensional dynamical systems. A main difficulty in the analysis of NFEs is posed by their nonlocal nature, which is typically represented in such models by the convolution of a synaptic kernel with a nonlinear transformation of the neuronal activity variable. NFEs often feature slowly-varying adaptation variables, which are highly relevant to the regulation of neuronal dynamics. A rigorous fast-slow analysis of these models has so far not been explored. More generally, mathematical research on infinite-dimensional fast-slow systems of differential equations appears scarce in comparison to the vast literature that is available for ODE models. I will present results on a functional analytic approach to the study of trajectories in the slow manifold of fast-slow NFEs. This approach relies on analyzing the behavior of bounded continuous solutions of the equation of perturbed motion at such trajectories. Such an approach has the advantage that it is closely related to methods based on exponential dichotomies for infinite-dimensional and non-autonomous dynamical systems. Therefore it could provide an integrated theoretical framework for multiple timescale dynamics in NFEs.

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MS50

Snaking of Contact Defects in the Brusselator

The Brusselator is one of the oldest systems studied in spatial dynamics, first conceived as a result of Turings landmark work on the formation of stripe patterns in the 1960's. Despite the decades and myriad studies since then, it remains a system of interest due to its ability to display a zoo of different complex behaviors. In this work we look at a newly discovered behavior, snaking of contact defects. Numerical studies by Tzou et al. (2013), found that an instability between two distinct types of stable oscillations allows for the production of contact defects: a temporally constant core region sitting in a temporally oscillating background. Their results suggest that these patterns form through a process called snaking. In this talk we will discuss how intuition from finite dimensional systems can be lifted, with some modifications, to prove the existence of these defects and some surprising results we have found so far.

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MS50

Slow Manifolds for Fast-Reaction PDEs

Fast-slow dynamical systems in finite dimension have been studied by many authors over the last decades. However, it is very challenging to transfer the results to infinite dimensions. In this talk we focus on fast-reaction systems in general Banach spaces and we extend the classical Fenichel theory to this infinite-dimensional setting. Using insights from the finite-dimensional case, we first transfer the notion of normal-hyperbolicity. We show that the solution of the fast-reaction system can be approximated by the corresponding slow flow of the limit system. Introducing an additional parameter that stems from a splitting in the slow variable space, we construct a family of slow manifolds and prove that the slow manifolds are close to the critical manifold. Moreover, the semi-flow on the slow manifold converges to the semi-flow on the critical manifold.

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MS50

A Geometric Singular Perturbation Analysis of Generalised Shock Selection Rules in Reaction-Nonlinear Diffusion Models

Reaction-nonlinear diffusion (RND) partial differential equations are a fruitful playground to model the formation of sharp travelling fronts, a fundamental pattern in nature. In this talk, we demonstrate the utility and scope of regularisation as a technique to investigate shock-fronted solutions of RND PDEs, using geometric singular perturbation theory (GSPT) as the main mathematical framework. In particular, we show that composite regularisations can be used to construct families of shock-fronted travelling waves sweeping out distinct generalised 'equal-area rules'. If time permits, we also discuss the spectral stability of these interpolated shockwaves. In particular, we determine that our regularised RND PDE admits nonlinearly stable shock-fronted travelling waves. The multiple-scale nature of the regularised RND PDE continues to play an important role in the analysis of the spatial eigenvalue problem.

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MS51

Cardiac Fibrillation Overview

Fibrillation is a highly lethal irregular rhythm of the heart with a major clinical-societal burden. The mechanisms involved in the highly disorganized patterns of electrical impulse propagation that characterize fibrillation are still poorly understood and its therapies are sub-optimal. The talk will present optical mapping data with frequency and phase domains processing of spatio-temporal patterns of cardiac electrical activity to improve understanding of the arrhythmia. Experimental evidence will be presented to demonstrate that complex activation patterns during fibrillation can depend on fast rotors which represent organized centers of self-sustained patterns of electrical impulses spinning at high frequencies. The universality of the rotors across mammals and some ionic factors that determine their dynamics, as well as remaining questions and challenges in clinical applications will be discussed.

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MS51

Overdrive Pacing in a Three-Dimensional Model

for Ventricular Fibrillation

Fibrillation is a dangerous state in the heart, in which fragmented and interacting electrical waves occur in the cardiac muscle. The usual therapy is to apply a strong electrical shock, but in recent years, the possibility to apply repeated external stimuli of smaller amplitude has been investigated. In our work, we numerically apply a periodic stimulation to a medium that exhibits negative filament tension. We find that whether or not the scroll waves are pushed to the boundary depends on a bifurcation parameter that tells if the filament orients itself perpendicular to the impeding wave train or not. Our 3D considerations are relevant for the development of low-voltage defibrillation strategies.

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MS51

Efficient Termination of Cardiac Arrhythmias Using Optogenetic Resonant Feedback Pacing

The control of cardiac arrhythmias has been demonstrated in optogenetic hearts using open loop control using single light pulses, global and structured illumination. Here we investigate the efficacy of optogenetic resonant feedback pacing in silico and ex vivo. We study the control of ventricular arrhythmias (VTs) in N=5 intact Langendorff-perfused murine hearts expressing ChR2 using two protocols: (i) a single light pulse (SP) (duration 10 and 100 ms, wavelength 470 nm) and (ii) resonant feedback pacing (RFP) with a sequence of global light pulses (duration 20 ms). The termination success rate is determined as a function of light intensity (LI) for both protocols. Corresponding numerical simulations of cardiac tissue are performed using the Bondarenko model in conjunction with a ChR2 model in a 2D domain 25x25 mm^2. Ex vivo experiments show, RFP pacing supersedes SP in termination efficacy of VTs (LI at 50% termination rate (LI50) RFP: $LI_{50} = 3$ W/mm , SP: $LI50 = 150$ W/mm or 300 W/mm). We observe efficient termination of VTs using RFP even at subthreshold LIs (no excitation wave is induced). Numerical simulations show a dose-response consistent with the experimental findings. At subthreshold LIs, simulations suggest that resonant feedback pacing result spatial-temporal modulation of excitability that induces spiral wave drift and subsequent arrhythmia termination. RFP enables effective termination of cardiac arrhythmias even at subthreshold LIs.

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MS51

Adapting the Timing of Pulse Sequences: Controlling Spiral Wave Chaos by Deceleration Pacing

The spatio-temporal dynamics during life threatening cardiac arrhythmias such as ventricular fibrillation is governed by a chaotic electrical excitation wave dynamics. Several novel defibrillation concepts are based on sequences of pulses of lower energy with the goal to terminate arrhythmias with reduced side effects in comparison to the conventional method. In many of these approaches, the temporal distance between consecutive pulses is often kept constant. We demonstrate in a numerical study, how adapting the temporal distances between pulses may significantly alter the success rate of pulse sequences.

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MS52

Multiscale Models of SARS-CoV-2 Infection

Designing control strategies for the COVID-19 epidemic requires multiscale understanding of individual infections, the probability of transmission through aerosol exposure, and the role of vaccination and testing in limiting an outbreak at the population level. In the first part of this talk, I will present models of within-host and aerosol dynamics in animals and humans infected with SARS-CoV-2. They will focus on the tradeoff between viral infectiousness and viral positivity, as well as the biases induced by the scarcity of data early in the individual's infection. In the second part, I will connect infected individuals' virus profile with transmission, testing strategies, and vaccination at the population level. Using multiscale models, we will predict testing-vaccination combination strategies best suited for limiting an outbreak with variants of increased transmissibility. Our findings can improve interventions.

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MS52

Modeling Immune Response Impact on Post-Treatment Interruption HIV Viral Dynamics

Antiretroviral therapy (ART) effectively controls HIV infection, suppressing HIV viral loads. Typically suspension of therapy is rapidly followed by rebound of viral loads to high, pre-therapy levels. Indeed, a recent study showed that approximately 90% of treatment interruption study participants show viral rebound within at most a few months of therapy suspension, but the remaining 10%, showed viral rebound some months, years, or maybe permanently, after ART suspension. Design of therapeutic interventions to expand this latter group are underway. An understanding of the heterogeneity in rebound dynamics, crucial in design of clinical trials to test these interventions, is lacking. We will discuss our branching process model to gain insight into these post-treatment dynamics relying on the interplay of latent reservoir dynamics and immune responses. Specifically we provide theory that explains both short- and long-term viral rebounds, and post-treatment control, via a branching process model with time-inhomogeneous rates, validated with data from Li et al. (2016). Our emphasis in this talk will be on divining impacts of immune responses, by considering interpreting the impact of covariates, such as treatment initiation time, on the survival curve. We will also provide an example of how our modeling can be used to inform HIV treatment suspension study design.

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MS52

Within-Host Antibody Dynamics Stabilize the Persistence of Foot-and-Mouth Disease in African Buffalo Populations

The interface between domesticated animals, humans, and wildlife is broadening on a global scale, creating novel environments for increased epidemics, pathogen spillovers, and pandemics (Plowright et al., 2017). Foot-and-mouth disease viruses (FMDV) are the most important livestock pathogen restricting international trade due to their high transmissibility between ungulates (Coetzer et al., 1994). In sub-Saharan Africa, wild buffalo (*Syncerus caffer*) act as a reservoir host for this pathogen, challenging its global eradication and affecting local economies (Thomson et al., 1992). Therefore, it is crucial to understand how these fast-spreading viruses persist in their reservoir populations. Previous work has looked at different mechanisms of persistence, such as transmission among susceptible calves, and from carrier animals, which retain the virus for several months after primary infection (Jolles et al., 2021). In this talk, we will present current modeling work concerning the propagation of FMDVs in their reservoir host, the dynamics for the loss of acquired immunity, and its role in the facilitation and stabilization of the persistence of this fast-spreading pathogen in wildlife populations.

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MS52

Estimating Waning of Vaccine-Induced Protection: a Simulation Study

Accurate estimation of the extent of waning of the vaccine-induced protection over time is an important public health need. The observed waning of vaccine effectiveness (VE) could be caused by a true waning of immunity, an apparent waning due to arising viral mutations allowing the virus to escape a part of vaccine-induced immunity, or could result from underlying population heterogeneities (e.g.frailty phenomenon). To understand how multiple factors may complicate our ability to estimate VE and to compare different statistical methods, we used an agent-based modeling framework linking within-host waning of protection and between-host SIR-based dynamics of the spread of an acute viral infection in a human population during one season. We found that the commonly used extension of the Cox proportional hazard model utilizing scaled Schoenfeld residuals was unreliable in capturing both the degree of fast waning and its functional form and identified the mathematical factors contributing to this unreliability. Partitioning time and including a time-vaccine interaction (TVI) term in the Cox model significantly improved the estimation of rapid VE waning. We further used the proposed TVI method to explore the net effect of competing heterogeneities.

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MS53

Data Driven Model Applied to Neuronal Dynamics

Neuronal synchronization plays an important role in brain function. It has been shown to be necessary for memory consolidation as well in locomotion. However, abnormal excessive synchronous neuronal activity can also be damaging as in the case of epileptic seizures, for example. Despite much research on epilepsy, there are still challenges predicting seizures prior to their onset. In this work we combine EEG recordings of the brains electrical activity, along with a phase detection method, to characterize abnormal neuronal dynamics during seizures. The phase locking value method is used to quantify synchronization among distinct brain areas during the seizure. We found that during the seizure, synchronization was more prevalent then prior or post seizure. Additionally, we developed a data driven model based on the phase of the EEG signals to predict seizures.

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MS53

Influence of Coupling Delays in Neuronal Networks

In this talk we discuss the stability of synchronization in networks of dynamical systems with strongly delayed connections. We obtain strict conditions for synchronization of periodic and equilibrium solutions. In particular, we show the existence of a critical coupling strength Kc, depending only on the network structure, isolated dynamics and coupling function, such that for large delay and coupling strength K ¡ Kc, the network possesses stable synchronization. The critical coupling Kc can be chosen independently of the delay for the case of equilibrium, while for the periodic solution, Kc depends essentially on the delay and vanishes as the delay increases. We observe that, for random networks, the synchronization interval is maximal when the network is close to the connectivity threshold. We also derive scaling of the coupling parameter that allows synchronization of large networks for different network topologies.

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MS53

A Quantitative Description of Thermally-Induced Calcium Dynamics in the AFD Neuron of C. Elegans

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 calcium dynamics of the AFD neuron when exposed to both linearly ramping and oscillatory temperature stimuli. Motivated by experiments from previous works, the peak time of the calcium response during simulations of pulse-like temperature inputs is also calculated for various combinations of the Arrhenius parameter values. Our results establish the first generative quantitative mathematical framework for thermally-induced calcium activity in the AFD neuron and form a foundation on which to build more biophysically-detailed models.

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MS53

Modulation Effects on Noisy Chaotic Neuronal Systems

Chaotic and stochastic processes, both yielding similar erratic behaviors are, in essence, the result of fundamentally different dynamics: chaotic systems are deterministic and stochastic systems are probabilistic. Despite their absolutely distinct roots, separating intermingled chaotic from stochastic processes poses a rather difficult challenge. In this work we analyze the behavior of a modulated neuronal nonlinear dynamical system responsible for the gastric function of crustaceans where chaos and stochasticity are intrinsically blended, producing outputs where mixed deterministic and probabilistic dynamics happen to be basically indistinguishable. We focus on the neuronal system responsible for the gastric function in crustaceans, with particular attention on the pyloric dilator neuron of the stomatogastric ganglion of the crab *Cancer borealis* under the action of neuromodulation. Our approach uses both a computational model without and with noise, and a biological experimental setting. The results we obtain show striking similarities between some of the outputs from the computational and from the experimental studies, despite the inherent difficulty of separating chaos from noise.

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MS54

Topological Instability in the Restricted 3 Body Problem

A major question in dynamical systems is to understand the mechanisms driving global instability in the 3 Body Problem, which models the motion of three bodies under gravitational interaction. The 3BP is called restricted if one of the bodies has zero mass and the other two have strictly positive masses m_0, m_1. In this limit problem the goal is to describe the motion of the massless body. We consider the Restricted Planar Elliptic 3 Body Problem (RPE3BP) where the massive bodies revolve one around each other in Keplerian ellipses. We prove that, for any values of the masses m_0, m_1 (except $m_0 = m_1$) a degenerate Arnold Diffusion Mechanism takes place in the RPE3BP provided the eccentricity of the massive bodies is small enough. More concretely, we build a transition chain of periodic orbits located in a (topological) Normally Hyperbolic Invariant Cylinder which is foliated by fully resonant invariant tori. This mechanism allows us to show that the RPE3BP exhibits topological instability: for any value of the masses m_0, m_1 (except $m_0 = m_1$), we build orbits along which the angular momentum of the massless body experiences an arbitrarily large variation provided the eccentricity of the orbit of the massive bodies is small enough. The setting in which we construct the Arnold Diffusion mechanism displays many features of the so called a priori stable case.

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MS54

Near Quasi-Integrable Hamiltonian Systems with Impacts

Near integrable Hamiltonian flows with impacts that respect the symmetries of the integrable structure, either globally or locally, provide new classes of non-smooth near integrable, or, respectively near Quasi-Integrable (QI), systems. While the level sets of the integrable impact systems are tori, QI systems include also level sets of genus 2 and higher. Ergodicity on levels sets is proved for some classes of QI Hamiltonian impact systems for a full measure of iso-energy level sets. Yet, their quantization suggests that their wavefunctions do not equidistribute in the configuration space in the large energy limit. Finally, the return maps for classical near-QI systems are shown to be piecewise smooth symplectic maps which are close to families of interval exchange maps and exhibit fascinating dynamics.

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MS54

Stable motions of high energy particles interacting via a repelling potential

The motion of N particles interacting by a smooth repelling potential and confined to a compact d-dimensional region is proved to be, under mild conditions, non-ergodic for all sufficiently large energies. Specifically, choreographic solutions, for which all particles follow approximately the same path close to an elliptic periodic orbit of the single-particle system, are proved to be KAM stable in the high energy limit. Finally, it is proved that the motion of N repelling particles in a rectangular box is non-ergodic at high energies for a generic choice of interacting potential: there exists a KAM-stable periodic motion by which the particles move fast only in one direction, each on its own path, yet in synchrony with all the other parallel moving particles. Thus, we prove that for smooth interaction potentials the Boltzmann ergodic hypothesis fails for a finite number of particles even in the high energy limit at which the smooth system appears to be very close to the Boltzmann hard-sphere gas.

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MS54

Symbolic Dynamics and Chaos in Galactic Refraction Billiards

A new type of dynamical model, describing the motion of a point-mass particle in an elliptic galaxy with a massive central core (such as, for example, a Black Hole), is presented. This kind of model belongs to the more general class of refraction billiards, which are particularly useful to describe the dynamics of particles under the action of discontinuous potentials. In our case, a refraction interface (a regular closed curve) separates a Keplerian potential with positive energy from a two-dimensional homogeneous harmonic potential. The dynamical properties of the system depend crucially on the geometric features of the interface: in particular, one can prove that, under generic assumptions on the interface, the system admits a symbolic dynamics. Moreover, by strengthening such hypotheses on the billiard's boundary, the actual chaoticity of (an invariant subset of) the system can be proved, as well as the absence of non-constant analytic first integrals of the motion and the presence of an infinite number of heteroclinic connections between hyperbolic fixed points.

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MS55

Reduction Strategy for Optimal Control of Stochastic Gross-Pitaevskii Equations

Physical applications involving Bose-Einstein condensates (BEC) often require that the initial condition be prepared in a specific complex state. Optimal control theory provides a reliable framework to prepare such a state while avoiding undesirable excitations, and, when applied to a time-dependent Gross-Pitaevskii equation (GPE) model of BEC in the presence of noise, results in a large computational problem. We propose a control method based on first reducing the problem, using a Galerkin expansion, from a stochastic partial differential equation to a low-dimensional stochastic Hamiltonian system. In this setting, solving the relevant Hamilton-Jacobi-Bellman equation is feasible, and will be demonstrated via numerical examples.

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MS55

Solitary Waves in Next Nearest Neighbor Fput Lattices

In this article, we consider atomic chains with next nearest neighbor interactions and construct small amplitude traveling waves for the system proposed by [Wattis, Approximations to solitary waves on lattices, III: the monatomic lattice with second-neighbour interactions]. We look at two cases of g and we see that for one case, we have an exponentially localized solution. 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 ODE's. In the second case, the solution develops a ripple as $x \to \infty$. We use the method originally developed by Beale for a capillary water wave problem to prove the existence of nanopterons solutions. The periodic wave solution is an essential part of our analysis.

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MS55

Mass and Spring Dimer Fput Nanopterons with Exponentially Small, Nonvanishing Ripples

Mass and spring dimer Fermi-Pasta-Ulam-Tsingou (FPUT) lattices are known to possess nanopteron traveling waves in relative displacement coordinates. Nanopterons are the superposition of a localized core and a small-amplitude periodic ripple; while it has been established that the ripples amplitude is small beyond all algebraic orders of the long wave parameter, more precise upper, and lower, bounds have not been known until recently. Methods from spatial dynamics enable the construction of nanopterons whose ripple amplitudes are both exponentially small and nonvanishing. This talk will give an overview of the spatial dynamics method and the various adaptations and generalizations needed to apply it to FPUT lattices, as well as interesting ancillary results obtained in the original position coordinates. Challenges in extending the method to nonsymmetric dimers and FPUT lattices with more complicated material heterogeneities than the dimer structure will also be discussed, as well as connections of these FPUT solution techniques to other, diverse lattice problems and systems of nonlocal differential equations.

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MS55

Stochastic Speed and Shape Corrections for Travelling Patterns in Random Media

We describe a framework to uncover the shape and speed corrections caused by noise-terms that can be both Lipschitz and non-Lipschitz. By using perturbative techniques, we avoid the need to use the comparison principle. In some cases it is no longer sufficient to use the standard linear operators associated to the deterministic travelling waves.

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MS56

Exact Finite-Dimensional Reduction for a Population of Noisy Oscillators and Its Link to Ott-Antonsen and Watanabe-Strogatz Theories

Populations of globally coupled phase oscillators are described in the thermodynamic limit by kinetic equations for the distribution densities, or equivalently, by infinite hierarchies of equations for the order parameters. Ott and Antonsen [Chaos, 18, 037113 (2008)] have found an invariant finite-dimensional subspace on which the dynamics is described by one complex variable per population. For oscillators with Cauchy distributed frequencies or for those driven by Cauchy white noise, this subspace is weakly stable and thus describes the asymptotic dynamics. Here we report on an exact finite-dimensional reduction of the dynamics outside of the Ott-Antonsen subspace. We show, that the evolution from generic initial states can be reduced to that of three complex variables, plus a constant function. For identical noise-free oscillators, this reduction corresponds to the Watanabe-Strogatz system of equations [Phys. Rev. Lett. 70, 2391 (1993)]. We discuss how the reduced system can be used to explore the transient dynamics of perturbed ensembles.

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MS56

Exact Finite-Dimensional Description for Networks of Globally Coupled Spiking Neurons

We consider large networks of globally coupled spiking neurons and derive an exact low-dimensional description of their collective dynamics in the thermodynamic limit. Individual neurons are described by the Ermentrout-Kopell canonical model that can be excitable or tonically spiking, and interact with other neurons via pulses. Utilizing the equivalence of the quadratic integrate-and-fire and the theta neuron formulations, we first derive the dynamical equations in terms of the Kuramoto-Daido order parameters (Fourier modes of the phase distribution) and relate them to two biophysically relevant macroscopic observables, the firing rate and the mean voltage. For neurons driven by Cauchy white noise or for Cauchy-Lorentz distributed input currents, we adapt the results by Cestnik and Pikovsky [arXiv:2207.02302 (2022)] and show that for arbitrary initial conditions the collective dynamics reduces to six dimensions. We also prove that in this case the dynamics asymptotically converges to a two-dimensional invariant manifold first discovered by Ott and Antonsen. We illustrate the exact six-dimensional dynamics outside the invariant manifold by calculating nontrivial basins of different asymptotic regimes in a bistable situation. Moreover, we shed light on collective oscillations when neural communication occurs via instantaneous, (a)symmetric pulses of finite width.

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MS56

Low-Dimensional Description for Ensembles of Identical Phase Oscillators Subject to Cauchy Noise

There are famous low-dimensional reductions for populations of globally forced and coupled phase oscillators, due to Watanabe and Strogatz and to Ott and Antonsen. Both these theories are restricted to the case of a coupling in the first harmonics of the phase. In this talk we first show that the OA description can be extended to populations of noisy oscillators, if the distribution of noise is a Cauchy one. Next, we extend the theory to the case of a multi-harmonic coupling and demonstrate, that stationary regimes for a coupling function that includes L harmonics, are fully parametrized by L complex parameters. The probability distribution of the phases is in this case a wrapped poly-Cauchy distribution.

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MS56

Continua of Equilibrium States in Globally Cou-

pled Ensembles

Global fields generated by ensembles of coupled oscillators and acting upon individual units in these ensembles are known to be responsible for many unusual kinds of collective behavior. Among the most striking examples is the Watanabe-Strogatz dynamics in ensembles of identical one-dimensional rotators: there, specific kind of coupling to the global field ensures existence of numerous constants of motion and allows for a drastic exact reduction in the number of degrees of freedom. Here, we discuss a simpler approach, restricted to the widespread situations in which the number of parameters (coordinates) defining the action of the global fields is smaller than the overall number of elements in the ensemble. In the phase space of such ensembles, high-dimensional manifolds composed of the equilibrium states can generically arise. Existence of these manifolds is not related to symmetries. In the simplest cases, such continua of steady states can be attracting or repelling as a whole; in general, however, their stability with respect to transversal perturbations varies in the course of the motion along the manifold. Remarkably, the suggested mechanism does not require that all oscillators are identical: the sufficiently strong global field is able to counteract diversity among the ensemble units and halt the temporal evolution.

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MS57

Distributions of inertial active Brownian particles in a trap

A harmonically trapped active Brownian particle exhibits two types of positional distributions – one has a single peak, the other has a single well – that signify steady-state dynamics with low and high activity, respectively. Adding inertia to the translational motion preserves this strict single peak/well classification of the densities but shifts the dividing boundary between the states in the parameter space. We characterize this shift in the dynamics for one spatial dimension by solving the static Fokker–Planck equation for the full joint distribution of the state space with both asymptotic and numerical methods

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MS57

Reflected Diffusions with Partial Annihilations on a Membrane

Mathematicians and scientists use interacting particle models to gain understanding of the emergence of macroscopic phenomena from microscopic laws of nature. In this talk, I will introduce a class of interacting particle systems that can model the transport of positive and negative charges in solar cells. To connect the microscopic mechanisms with the macroscopic behaviors at two different scales of observations, we prove the hydrodynamic limits and the fluctuation limits for these systems. Proving these two types of limits represents establishing the law of large numbers and the central limit theorem, respectively, for the time-trajectory of the particle densities. We show that the hydrodynamic limit is a pair of deterministic measures whose densities solve a coupled nonlinear heat equations, while the fluctuation limit can be described by a Gaussian Markov process that solves a stochastic partial differential equation.

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MS57

Anisotropic Active Brownian Particle with a Fluctuating Propulsion Force

The active Brownian particle (ABP) model describes a swimmer, synthetic or living, whose direction of swimming is a Brownian motion. The swimming is due to a propulsion force, and the fluctuations are typically thermal in origin. We present a two-dimensional model where the fluctuations arise from nonthermal noise in a propelling force acting at a single point, such as that due to a flagellum. We take the overdamped limit and find several modifications to the traditional ABP model. Since the fluctuating force causes a fluctuating torque, the diffusion tensor describing the process has a coupling between translational and rotational degrees of freedom. An anisotropic particle also exhibits a mass-dependent noise-induced drift, which does not disappear in the overdamped limit. We show that these effects have measurable consequences for the long-time diffusivity of active particles, in particular adding a contribution that is independent of where the force acts. If time permits, I'll introduce some recent results from a three-dimensional ABP model. This is joint work with Professor Jean-luc Thiffeault from the University of Wisconsin - Madison.

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MS57

Stiffening of An Active Solid

This work deals with the mechanical properties of an active elastic solid defined as a two-dimensional network of active stochastic particles interacting by nonlinear hard springs. It is numerically found that when activity in the system is turned on, the active solid stiffens, thus deviating from equilibrium mechanics. Interestingly, the active forces individually acting along the solid are stochastic; thus no preferred direction is imposed. This effect could be potentially used to construct novel active materials whose mechanical properties could be tuned according to their needs. A collective behavior, density fluctuation, and internal stresses analysis to the active solid in the absence of an external stress, is also carried out.

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MS58

Nonlinear Dynamics of Collective Belief Formation

In this work, we study the dynamics of belief formation on multiple topics in a network of communicating agents who share a common belief system. We model belief updates as a nonlinear dynamic process in which individuals apply a saturating nonlinearity to social information about each topic. We prove that a deadlock-breaking bifurcation in the model gives rise to various interpretable belief-forming behaviors in the group, including convergence to one of several multistable equilibria and the onset of persistent oscillations. We illustrate how various spectral properties of the communication graph and the belief system graph inform the structure of the emergent beliefs in the group post-bifurcation.

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MS58

Smart Self-Propelled Particles: a Framework to Investigate Spatially-Embedded Decision-Making

Decision-making and movements of single animals or groups of animals are often treated and investigated as distinct processes. However, many decisions are taken by actually moving to achieve a goal (e.g. to feed), given several spatial and locomotor constraints. To fully understand the rational of decisions embedded in an environment, it is therefore instrumental to develop theories of spatial decision-making. Here, I introduce the smart self-propelled particles framework, specifically developed to address this issue, by combining self-propelled particles and cognitive agents. Ultimately, this framework sheds light on the optimal movements, behaviours and social interactions of animals achieving spatially-embedded tasks.

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MS58

Emergence of Polarization in a Sigmoidal Bounded-Confidence Model of Opinion Dynamics

We propose a nonlinear bounded-confidence model (BCM) of continuous-time opinion dynamics on networks with both persuadable individuals and zealots. The model is parameterized by a scalar γ, which controls the steepness of a smooth influence function encoding the relative weight that nodes place on the opinions of other nodes. When $\gamma = 0$, this influence function exactly recovers Taylors averaging model; when $\gamma \to \infty$, the influence function converges to that of a modified HegselmannKrause (HK) BCM. Unlike the classical HK model, our smoothed bounded-confidence model (SBCM) is smooth for any finite γ. We show that the set of steady states of our SBCM is qualitatively similar to that of the Taylor model when γ is small and that the set of steady states approaches a subset of the set of steady states of a modified HK model as $\gamma \to \infty$. In several special graph topologies, we give analytical descriptions of important features of the space of steady states. A notable result is a closed-form relationship between the stability of a polarized state and the graph topology in a simple model of echo chambers in social networks. Because the influence function in our BCM is smooth, we are able to study it with linear stability analysis, which is difficult to employ with the usual discontinuous influence functions in BCMs.

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MS59

Structured Learning of Koopman Generators via Koopmanizing Flows

In this talk, the concepts surrounding *Koopmanizing Flows* are presented a continuous-time framework for supervised learning of linear predictors for a class of nonlinear dynamics. In the models construction a latent diffeomorphically related linear system unfolds into a linear predictor through the composition with a monomial basis. The lifting, its linear dynamics and state reconstruction are learned simultaneously, while the structure admits an unconstrained parameterization of Hurwitz matrices that ensures asymptotic stability regardless of the operator approximation accuracy. The superior efficacy of *Koopmanizing Flows* is demonstrated in comparison to a state-of-the-art method on the well-known LASA handwriting benchmark. Through extensions towards an LQR control design for nonlinear systems, the method exhibits improved performance compared to related methods based on continuous-time linear predictor models.

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MS59

An Operator Theoretic Approach to Computing Invariant Sets

Invariant sets enable a reductionist analysis of nonlinear systems. Hence, there is a plethora of algorithms for the approximation of these geometric objects. In contrast to conventional Lyapunov-based approaches, we tackle this problem from a Koopman operator perspective. It is known that every invariant set corresponds to a level set of a Koopman eigen-function at 1. Yet, the approximation of the Koopman operator obtained from Dynamic Mode Decomposition (DMD) is not guaranteed to have an eigenvalue at 1. Our contribution is to remedy this defect by simply requiring that DMD be consistent along known fixed points and limit cycles. By duality, this constraint induces eigen-functions with eigen-value 1. The associated optimization routine is an affinely constrained least-squares problem which makes its computational cost comparable to the usual DMD formulation. Finally, we numerically demonstrate that the level set of an induced eigen-function at 1 correlates with the basin of attraction of the corresponding geometric invariant.

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MS59

Bernstein Polynomial Approximations of the Koopman Operator

This talk will present new results on the error bounds of the Koopman operator approximation obtained through a projection on Bernstein polynomials. Rates of convergence and error bounds for estimates of the Koopman operator will be given in various contexts corresponding to different levels of a priori knowledge on the flow generated by the dynamical systems. In particular, the main results are expressed in terms of modulus of continuity, modulus of continuity with the derivative of the function, and by means of Lipschitz maximal function. The order of approximation will be characterized for each case. Finally, numerical experiments will be presented to support the theoretical approximation results.

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MS60

Why Americans Purchase Guns? Complex System Analysis and Discovery from Small Data

Firearm violence is a major public health crisis in the U.S., where more than 200 people sustain a nonfatal firearm injury and more than 100 people die from it every day. In spite of these unsettling figures, Americans increasingly seek to purchase firearms. In order to thoroughly study why Americans purchase firearms and how access to firearms is associated with different outcomes of harm, highly-resolved data on firearm possession and the motivations to acquire them are needed. At present, such measurements are not readily available. In this talk, innovative methods to estimate firearm ownership and quantify potential drivers of firearm acquisition on a state level are presented. The time series of each variable is constructed and assigned to a complex network, where each U.S. state is represented by a node. Causal analysis is performed to disentangle relationships within the system and infer the factors driving firearm purchase.

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MS60

Using Optimal Foraging Theory to Infer How Groups Make Collective Decisions

Studying animal behavior as collective phenomena is a powerful tool for understanding social processes, including group coordination and decision-making. However, linking individual behavior during group decision-making to the preferences underlying those actions poses a considerable challenge. Optimal foraging theory, and specifically the marginal value theorem (MVT), can provide predictions about individual preferences, against which the behavior of groups can be compared under different models of influence. A major strength of formally linking optimal foraging theory to collective behavior is that it generates predictions that can easily be tested under field conditions. This opens the door to studying group decision-making in a range of species; a necessary step for revealing the ecological drivers and evolutionary consequences of collective decision-making.

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MS60

Stochastic Dynamics of Individual and Social Patch Foraging

Nearly all animals forage to acquire energy for survival through efficient search and resource harvesting. We develop a normative theory of patch foraging decisions, showing how individuals and social groups statistically infer patch resource yields using sequential updating, proposing mechanisms by which foraging behaviors emerge in the face of uncertainty. Patch departure decisions are triggered when the certainty of the patch type or the estimated yield of the patch falls below a threshold. Uncertainty leads patch-exploiting foragers to overharvest (underharvest) patches with initially low (high) resource yields in comparison with predictions of the marginal value theorem. In social groups, we model information sharing by considering both intermittent pulsatile coupling (only communicate decision to leave) and continuous diffusive coupling (communicate throughout the deliberation process). Pulsatile coupling can lead to high foraging efficiency, but this requires fine tuning of strategy parameters, while diffusive coupling generates moderate foraging efficiency, that is robust to mistuning. Our model establishes a social patch foraging framework to identify deliberative decision strategies and forms of social communication, and to allow model fitting to field data from foraging animal groups. These results extend optimal foraging theory and motivate a variety of behavioral experiments investigating patch foraging behavior.

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MS60

The Geometry of Decision-Making in Individuals and Collectives

Choosing among spatially-distributed options is a central challenge for animals, from deciding among alternative potential food sources or refuges, to choosing with whom to associate. Despite this, most studies have focused on the outcome of decisions (i.e. which option among alternatives is chosen), as well as the time taken to make decisions, but seldom on the movement of animals throughout the decision-making process. Motion is, however, crucial in terms of how space is represented by organisms during spatial decision-making. In this talk, I will highlight results from recent work, where we reveal the existence of fundamental geometrical principles that result from the inherent interplay between movement and organisms internal representation of space. We find that animals spontaneously reduce the world into a series of sequential binary decisions, a response that facilitates effective decision-making and is robust both to the number of options available, and to context, such as whether options are static (e.g. refuges) or mobile (e.g. other animals). We present evidence that these same principles, hitherto overlooked, apply across scales of biological organization, from individual to collective decision-making.

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MS61

Koopman Operator Methods for Analysis and Prediction of Arctic Sea Ice Dynamics

Recent reports have noted the rapid decay of sea ice concentration (SIC) in the Barents Sea region of the Arctic, indicative of a potential "tipping point" with the expected increases in global temperature. We present results based on Koopman mode analysis (KMA) of NSIDC SIC data showing Koopman eigenvalues corresponding to exponential decrease in SIC in the Barents Sea. Specifically, we show that a Koopman mode exhibiting exponential decay is consistently detected from KMA applied to observational satellite data from both the entire Arctic region and to only the Barents Sea. This mode is not found when the Barents Sea SIC is excluded from the training data, indicating that the identified decaying dynamics are spatially localized to the Barents Sea. The geographic distribution of Koopman modes corresponding to the identified exponential decay eigenvalues is also found to have a spatial locus in the Barents Sea region. We conclude that the Barents Sea is undergoing a nonlinear decrease in SIC, which may be a signature of a potential tipping point.

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MS61

Data-Centric Approach to Identify the Non-Polynomial Nonlinear Dynamics of Power Grids

We propose an analytical construction of observable functions in the extended dynamic mode decomposition (EDMD) algorithm. The choice of observable functions is fundamental for the application of EDMD to nonlinear problems arising in systems and control. Existing methods either start from a set of dictionary functions and look for the subset that best fits the underlying nonlinear dynamics or they rely on machine learning algorithms to "learn' observable functions. Conversely, we start from the dynamical system model and lift it through the Lie derivatives, rendering it into a polynomial form. This proposed transformation into a polynomial form is exact, and it provides an adequate set of observable functions. The strength of the proposed approach is its applicability to a broader class of nonlinear dynamical systems, particularly those with nonpolynomial functions and compositions thereof. Moreover, it retains the physical interpretability of the underlying dynamical system and can be readily integrated into existing numerical libraries. The proposed approach is illustrated with an application to electric power systems. The results demonstrate the effectiveness of the proposed procedure in off-attractor nonlinear dynamics for estimation and prediction; the observable functions obtained from the proposed construction outperform methods that use dictionary functions comprising monomials or radial basis functions.

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MS61

A Koopman Operator Theoretic Approach for Studying Deep Learning

Deep learning exists as something of a contradiction. On the one hand, there has been an immense amount of practical development on methods that are able to perform highly complex tasks with remarkable success. On the other hand, there is a great lack of theoretically grounded understanding of all but the simplest machine learning paradigms. An outstanding problem then is to bridge this gap and provide meaningful, quantitative analysis of state-of-the-art deep learning models that can be connected to theory. In this talk, I will argue that Koopman operator theory, by its nature of being a data-driven dynamical systems framework that is intimately connected to the geometrical state-space theory that emerged over the past century, is a natural choice for achieving this bridging. I will highlight the success recent work that has used Koopman operator theory to analyze, optimize, and design deep neural networks has found and discuss open questions in this growing subfield.

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Prediction and Control of Swarm Formation in Unknown Nonlinear Potential Using Dynamic Mode Decomposition

Formation control in multi-agent system has earned significant research interests in both theoretical aspect and applications over the past two decades. However, the study on how the external environment shapes swarm formation dynamics, and the design of formation control algorithm for multi-agent system in nonlinear external potential have not been rigorously investigated. In this research, we present a formation control algorithm for agents traveling in an unknown nonlinear external potential with only relative local informations to its neighbor. Agent's trajectory is considered as a discrete dynamical system with input. Dynamic Mode Decomposition with control is used to predict the relative information and guide the agent's trajectory.

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MS62

The Continuing Conundrums of Snaking

Localized spatial patterns arise in many natural processes: buckled shells, spots in autocatalytic chemical reactions, crime hotspots, localized fluid structures, and vegetation spots are prominent examples that have attracted much attention. These structures can exhibit snaking: in parameter space, the localized states lie on a vertical sine-shaped bifurcation curve so that the width of the underlying pattern, such as hexagons or rolls, increases as we move up along the bifurcation curve. I will discuss several scenarios that challenge our understanding of snaking in bistable systems. The first scenario focuses on the difference between snaking on regular lattices and on unstructured or random graphs and networks. The second scenario addresses snaking of time-periodic localized structures on graphs and the real line, including defects that connect a spatially homogeneous temporal oscillation in the far field with a stationary spatially periodic Turing pattern in their core.

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MS62

Mechanochemical Pattern Formation: Far-From-Equilibrium Patterns on a Deforming Surface

The appearance of Turing patterns is generally believed to depend on an underlying activator-inhibitor mechanism. However, in a number of biological applications, the experimental identification of these components has been problematic. The hypothesis of mechano-chemical interaction, where the morphogen and the surface dynamically interact, provides an alternative to the activator-inhibitor paradigm. We present a mechano-chemical model, where the surface on which the pattern forms being dynamic and playing an active role in the pattern formation, effectively replaces the inhibitor. We show how existing ideas and techniques for the rigorous analysis of far-from-equilibrium patterns can be extended to the mechano-chemical context, and demonstrate the use of geometric singular perturbation theory in the construction of patterns on (and of) a planar curve. We highlight and discuss mathematical challenges posed by this particular interplay of partial differential equations and differential geometry. Joint work with Anna Marciniak-Czochra, Moritz Mercker (U. Heidelberg), and Daphne Nesenberend (U. Leiden).

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MS62

Eckhaus Instability in the Lugiato-Lefever Model

We study theoretically the primary and secondary instabilities undergone by the stationary periodic patterns in the Lugiato-Lefever equation in the focusing regime. Direct numerical simulations in a one-dimensional periodic domain show discrete changes of the periodicity of the patterns emerging from unstable homogeneous steady states. Through continuation methods of the steady states we reveal that the system exhibits a set of wave instability branches. The organisation of these branches suggests the existence of an Eckhaus scenario, which is characterized in detail by means of the derivation of their amplitude equation in the weakly nonlinear regime. The continuation in the highly nonlinear regime shows that the furthest branches become unstable through a Hopf bifurcation

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MS62

Spatial Instabilities As a Consequence of Tur-

ing Or Transcritical Bifurcations in Bulk-Surface Reaction-Diffusion Equations on a Sphere

Different real-world models show Turing instability patterns. These patterns have caught the interest of many researchers since their existence reveals conditions under which some variables can show complicated non-homogeneous behavior throughout space. So far, much work has been done on Turing bifurcations on the line. Some insights have been developed on conditions under which they can occur and their criticality. The latter concept provides an idea of the stability of the patterns that arise from a homogeneous steady state at the corresponding bifurcation point. However, not much has been said about different, complicated geometries. My talk will be about Turing patterns on general reaction-diffusion equations with n components on bulk-sphere systems. I will show the conditions required by these systems to go through a Turing bifurcation and provide a way to know its criticality. Besides, I will show some results obtained after applying the theory to a model formulated in this geometry, together with some interesting insights revealed by the theoretical study.

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MS63

Learning Invariant Statistics of Ergodic Ito Diffusions

In this talk, I will discuss recent works in understanding the problem of learning invariant properties of ergodic Ito diffusion from time series. The objective is to understand to which extent the invariant statistics of an underlying dynamical system can be recovered by an approximate dynamical model identified from a supervised learning framework. Using the perturbation theory of ergodic Markov chains and the linear response theory, we identify sufficient conditions for a linear dependence of the errors in the estimation of one-point and two-point invariant statistics on the error in the learning of the drift and diffusion coefficients. I will examine these mathematical conditions on two well-understood learning algorithms, the kernel-based spectral regression method and the shallow random neural networks with the ReLU activation function, and provide theoretical error bounds that depend on the number of training data, dimension of the phase space, complexity of the hypothesis space, and time discretization error.

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MS63

Optimal Transport of Directed Graphs via Transition Couplings

In this talk I will discus NetOTC, a procedure for the comparison and soft alignment of weighted networks. Given two networks and a cost function relating their vertices, NetOTC uses ideas from dynamics to find an appropriate coupling of their associated random walks having minimum expected cost. The minimizing cost provides a numerical measure of the difference between the networks, while the optimal transport plan itself provides interpretable, probabilistic alignments of the vertices and edges of the two networks. I will discuss a number of theoretical properties of NetOTC that support its use, including metric properties of the minimizing cost and its connection with short- and long-run average cost. In addition, we introduce a new notion of factor for weighted networks, which may be viewed as model reductions for networks, and establish a close connection between factors and NetOTC. Complementing the theory, I will present simulations and numerical experiments showing that NetOTC is competitive with, and sometimes superior to, other optimal transport-based network comparison methods in the literature. In particular, NetOTC shows promise in identifying isomorphic networks using a local (degree-based) cost function.

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MS63

Machine-Learning-Based Spectral Methods for Partial Differential Equations

Spectral methods are an important part of scientific computing's arsenal for solving partial differential equations (PDEs). However, their applicability and effectiveness depend crucially on the choice of basis functions used to expand the solution of a PDE. The last decade has seen the emergence of deep learning as a strong contender in providing efficient representations of complex functions. In the current work, we present an approach for combining deep neural networks with spectral methods to solve PDEs. In particular, we use a deep learning technique known as the Deep Operator Network (DeepONet) to identify candidate functions on which to expand the solution of PDEs. We have devised an approach that uses the candidate functions provided by the DeepONet as a starting point to construct a set of functions that have the following properties: (1) they constitute a basis, (2) they are orthonormal, and (3) they are hierarchical, i.e., akin to Fourier series or orthogonal polynomials. We have exploited the favorable properties of our custom-made basis functions to both study their approximation capability and use them to expand the solution of linear and nonlinear time-dependent PDEs. The proposed approach advances the state of the art and versatility of spectral methods and, more generally, promotes the synergy between traditional scientific computing and machine learning.

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MS63

Dimensionality Reduction by Level Set Learning

Approximating high-dimensional functions is challenging due to the curse of dimensionality. Inspired by the Nonlinear Level set Learning method that uses the reversible residual network, we developed a new method, Dimension Reduction via Learning Level Sets, for function approximations. It contains two major components: one is the pseudo-reversible neural network module that effectively transforms high-dimensional input variables to low-dimensional active variables, and the other is the synthesized regression module for approximating function values based on the transformed data in the low-dimensional space. Numerical experiments will be presented to demonstrate the proposed method.

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MS64

Monomolecular Networks in Stochastic Environment

Stochastic reaction networks are mathematical models heavily utilized in biochemistry. Usually it is assumed the rates at which biochemical transformations occur only depend on the current chemical configuration. Motivated by biological applications, in this study we considered the more general case of the rates depending on both the current configuration and another stochastic process. We study the positive recurrence of this more general model, and under certain conditions characterize the stationary distribution (when it exists) as a mixture of Poisson distributions, which is uniquely identified as the law of a fixed point of a stochastic recurrence equation. This recursion can be utilized for the statistical computation of moments and other distributional features.

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MS64

Mixing Times for Two Classes of Stochastically Modeled Reaction Networks

The past few decades have seen robust research on questions regarding the existence, form, and properties of stationary distributions of stochastically modeled reaction networks. When a stochastic model admits a stationary distribution an important practical question is: what is the rate of convergence of the distribution of the process to the stationary distribution? There has been a notable lack of results related to this rate of convergence in the reaction network literature. This work begins the process of filling that hole in our understanding. In this presentation, we show how to characterize this rate of convergence, via the mixing times of the processes, for some classes of stochastically modeled reaction networks. Specifically, by applying Foster-Lyapunov criteria and spectral gaps we establish exponential ergodicity for three classes of reaction networks.

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MS64

Multistationarity and Absolute Concentration Robustness in Reaction Networks

Reaction networks are commonly used to model a variety of physical systems ranging from the microscopic world like cell biology and chemistry, to the macroscopic world like epidemiology and evolution biology. Reaction networks arising in applications often exhibit multistationarity-that is, the capacity for two or more steady states. This property is important as it is often associated with the capability for cellular signaling and decision-making. Another biologically relevant property that reaction networks can have is absolute concentration robustness (ACR), which refers to when a steady-state species concentration is maintained even when initial conditions are changed. In this project, our driving motivation is to explore the relationship between the two properties and investigate the prevalence of networks with either property. Our analysis focuses on two ends of the network-size spectrum: small networks with a few species and large networks with many species.

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MS64

Asymptotic Analysis for Stationary Distributions of Scaled Reaction Networks

In this talk, the stationary distributions of a sequence of reaction networks equipped with scaling kinetics are studied. Consider a stochastically complex balanced network. Under an appropriate scaling of the kinetics, scaled networks are still complex balanced with a limit in the space of probability distributions. Furthermore, in the non-interacting setting, under a mild condition, the limit is a stationary distribution of the graphical reduction of the original network by eliminating non-interacting species.

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MS65

Large Heteroclinic Networks in Low Dimension

The construction of heteroclinic networks whose nodes and connections can be seen as vertices and edges in a given directed graph has been addressed previously. One of the construction methods, called the cylinder method, places the heteroclinic network in a state space of very high dimension since it uses one additional dimension per connection. We show that it is possible to construct heteroclinic networks corresponding to graphs where each vertex has two outgoing edges (connecting to the two subsequent vertices under some ordering for the vertices) so that (i) the nodes are all on the same coordinate axis, (ii) the vector field is polynomial, (iii) the heteroclinic networks are quasi-simple, and (iv) the state space has dimension at most 6, regardless of the number of vertices in the graph. Some of these heteroclinic networks include the Rock-Scissors-Paper network and the Rock-Scissors-Paper-Lizard-Spock network. Heteroclinic networks constructed from other types of graphs require a state space of dimension at most equal to the number of nodes plus one. Although this is not a fixed bound on the dimension of state space, it is much lower than the dimension indicated in the usual construction. For example, the Petersen graph can be realised with our construction in dimension 11 (rather than 31). The talk will end with a brief mention of the dynamics near heteroclinic networks using our construction. This is work in progress joint with Alexander Lohse.

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MS65

Switching Near Heteroclinic Networks as a Piecewise-Smooth Dynamical System

A heteroclinic cycle is an invariant structure in a dynamical system composed of a sequence of saddle equilibria and heteroclinic orbits connecting them in a cyclic manner. Near an attracting heteroclinic cycle, trajectories spend increasingly longer periods of time in the vicinity of one equilibrium before making a rapid transition to the next. Although heteroclinic orbits are often of high codimension, these structures can be robust in systems with appropriate symmetries. Systems with heteroclinic cycles can be used to model intransitive interactions and intermittent phenomena. A heteroclinic network is the connected union of a collection of heteroclinic cycles. Near a heteroclinic network, trajectories may asymptote onto one component cycle, possibly making a finite number of switches between cycles before doing so. Trajectories may also asymptote onto a larger subset of the network by cycling between cycles in regular or irregular sequences. The stability regions of different asymptotic behaviour can form interesting structures in parameter space with complicated patterns, including Farey-like concatenation and arbitrarily long, sometimes infinite, chains of sequences of cycling between cycles. In this talk, we will describe work combining the usual methods of analysing a heteroclinic network with tools from piecewise-smooth dynamical systems theory to investigate switching and cycling near heteroclinic networks and help us understand these patterns and structures.

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MS65

Heteroclinic Bifurcations: "Large' Strange Attractors

In this talk, we study bifurcations associated to heteroclinic networks. We are interested in "large' strange attractors in the terminology of Broer, Sim and Tatjer (Nonlinearity, 667–770, 1998), which are not confined to a"small' portion of the phase space. We focus on two different configurations: the first one involves the destruction of a torus; the other is connected to heteroclinic tangles. The proof of the existence of strange attractors relies on the analysis of the corresponding 1D reduction (the singular limit).

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MS65

Cycling Behaviour and Spatial Structure in a Heteroclinic Network Model of Rock–Paper–Scissors–Lizard–Spock

The well-known game of Rock–Paper–Scissors can be used as a simple model of competition between three species. When modelled in continuous time using ordinary differential equations, the resulting system contains a heteroclinic cycle between the three equilibrium solutions that represent the existence of only a single species. The game can be extended in a symmetric fashion by the addition of two further strategies ('Lizard' and 'Spock'): now each strategy is dominant over two of the other four strategies, and is dominated by the remaining two. The ODE model contains coupled heteroclinic cycles forming a heteroclinic network. We develop a technique, based on the concept of fragmentary asymptotic stability, to understand the stability of arbitrarily long periodic sequences of visits made to the neighbourhoods of the equilibria. The regions of stability form a complicated pattern in parameter space [Postlethwaite & Rucklidge, Nonlinearity (2022) https://doi.org/10.1088/1361-6544/ac3560]. By adding spatial diffusion, we extend to a partial differential equation model and investigate the spatiotemporal evolution of these periodic itineraries.

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MS66

Spatial-temporal Organization of Cardiac Fibrillation

Cardiac fibrillation is an electro-mechanic dysfunction of the heart that is driven by complex three-dimensional electrical excitation waves, resulting in incoherent mechanical contraction, loss of pumping function, and risk of sudden cardiac death. The nonlinear dynamics of vortex-like rotating waves play an essential role in the spatial-temporal organization of fibrillation. However, the visualization of these rotors, their interaction with each other and with the three-dimensional heterogeneous anatomical substrate remains a significant scientific challenge. In our talk, we will discuss the nonlinear dynamics of electrical and mechanical rotors during ventricular fibrillation. We will also address the application of rotor mapping using high-resolution 4D ultrasound for novel diagnostic and therapeutic approaches including arrhythmia control.

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MS66

Complexity Analysis of Electrical Activity During Endocardial and Epicardial Biventricular Mapping of Ventricular Fibrillation

Ventricular fibrillation (VF) is a lethal cardiac arrhythmia that is a significant cause of sudden cardiac death. Comprehensive studies of spatiotemporal characteristics of VF rhythm are challenging to perform, and thus, data is limited. We aimed to characterize the organization of electrical activity throughout VF using intracardiac electrograms during biventricular mapping of the endocardium (ENDO) and epicardium (EPI) in acute canine studies. VF was sequentially mapped in 4 canine hearts, using the CARTO mapping system, and the progression of VF at 3 discrete post-induction time intervals: just after induction of VF to 15 minutes, 15 to 30 minutes, and 30 to 45 minutes was considered. Linear Discriminant Analysis model and traditional cycle lengths (CL) and the regularity indices (RI) approaches were applied to all recorded intracardiac electrograms to quantify the spatiotemporal organization of VF. We demonstrated the presence of organized activities in the EPI as VF progresses, contrary to the ENDO, where the activity stays disorganized. The shortest CL always occurred in the ENDO, especially the RV, indicating faster VF activity and the presence of VF drivers. The highest RI was found in the EPI in all hearts for all VF stages, indicating spatiotemporal consistency of RR intervals.

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MS67

Discussion of Short Term Synaptic Plasticity in Mean Feld Models

We will use the last speaker slot to discuss ways to incorporate the experimentally determined STP map into mean field models, and possible implications of the results.

All Attendees
NA
NA

MS67

Exact Mean-Field Models for Spiking Neural Networks with Adaptation

We derive and analyze a set of exact mean-field equations for the neural network with spike frequency adaptation. Specifically, our model is a network of Izhikevich neurons. Previous work deriving a mean-field model for this type of network, relied on the assumption of sufficiently slow dynamics of the adaptation variable. However, this approximation did not succeed in establishing an exact correspondence between the macroscopic description and the realistic neural network, especially when the adaptation time constant was not large. The challenge lies in how to achieve a closed set of mean-field equations with the inclusion of the mean-field dynamics of the adaptation variable. We address this problem by using a Lorentzian ansatz combined with the moment closure approach to arrive at a mean-field system in the thermodynamic limit. The resulting macroscopic description is capable of qualitatively and quantitatively describing the collective dynamics of the neural network, including those where the individual neurons exhibit asynchronous tonic firing and synchronous bursting. We extend the approach to a network of two populations of neurons and discuss the accuracy and efficacy of our mean-field approximations by examining all assumptions that are imposed during the derivation. Our numerical bifurcation analysis reveals bifurcations not previously observed in the models, including a novel mechanism for emergence of bursting in the network.

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MS67

Derivation of Closed-Form Mean-Field Equations from Spiking Neural Networks with Synaptic Dynamics

Neurons in the brain interact via synapses, leading to the emergence of complex macroscopic dynamics. Synaptic short-term plasticity (STP) plays a crucial role in shaping these dynamics. To study the role of synaptic STP for macroscopic neural dynamics, methods from mean-field theory can be applied that allow the derivation of mean-field equations from the underlying neural network equations. Importantly, the derivation of these mean-field equations requires the simplifying assumption of all-to-all coupling between neurons. Under this assumption, all neurons in the studied network receive the same mean-field input. The derivation of closed-form mean-field equations requires finding an expression for this input that is neuron-independent. This is a hard problem in neural networks with synaptic STP. In this talk, I will address this problem in the context of the Ott-Antonsen ansatz [Ott and Antonsen, 2008, Chaos] and the Lorentzian ansatz [Montbriò et al. 2015, PRX], two mathematically equivalent approaches for deriving the mean-field equations for networks of all-to-all coupled phase oscillators and spiking neurons, respectively. I will lay out the problems with treating synaptic STP via these approaches and present approximate solutions for these problems, summarizing recently published work [Gast et al. 2020, Neural Computation; Gast et al. 2021, PRE, Gast et al. 2022, arXiv].

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MS67

Synapse Dependent Synaptic Plasticity Applied to Coupled Excitatory and Inhibitory Neurons in Hippocampus

Short term synaptic plasticity (STP) is synapse specific, and we built a model for STP at a pyramidal cell-OLM synapse in hippocampus, using data from single cell experiments. The response of the OLM cell is frequency dependent, which implies a kind of memory stored in the competing mechanisms of the vesicle depletion and calcium build-up. The model can be tuned to mimic various sorts of synapses, with different frequency-response properties. In this talk, I will examine its effect on the dynamics of a coupled excitatory and inhibitory cell network, as in the original experiments, as well as variations. We hope to incorporate these as building blocks in a mean-field model, and we will be able to discuss this in more detail during the last block of the session.

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MS68

Coordination of Endocrine Cell Networks

There are five types of endocrine cells in the anterior pituitary gland, each secreting one or more hormones that affect downstream glands and tissues throughout the body. These pituitary cells are electrically active, and it is now known that lactotrophs, corticotrophs, and somatotrophs form networks via gap junctions that provide electrical coupling among cells of each type. The behavior of these structural networks can be characterized by functional networks based upon florescence imaging of intracellular calcium. In this presentation, we discuss the relationship between structural and functional networks of coupled pituitary cells, and how the positioning of electrically bursting cells relative to spiking cells within the network can influence the level of hormone secretion from the network.

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MS68

Estimating Impaired Insulin Secretion with Uncertainty Quantification in Patients with Cystic Fibrosis

Cystic fibrosis (CF) is a life-limiting genetic condition in which a genetic mutation causes thick, dry mucous to accumulate in narrow passages throughout the body, including in the pancreas and lungs. CF-related complications in the pancreas lead to damaged beta cells and an insufficient insulin response to increased plasma glucose concentrations. The resulting dysglycemia can develop into cystic fibrosis-related diabetes (CFRD), the most common comorbidity in CF. If the insulin secretion rate (ISR) during an oral glucose tolerance test (OGTT) is known, the responsivity of beta cells to a metabolic stimulus can be quantified using an established modeling approach. However, ISR cannot be measured directly during an OGTT, so reliable methods for estimating ISR profiles are needed. Our statistical model infers the distribution of continuous ISR profiles from an individuals discrete C-peptide data using a differential model of C-peptide dynamics that includes ISR as a forcing function. By modeling ISR as a Gaussian process and leveraging the linear structure of the forward transformation, a closed-form approximation of the ISR profile is obtained from a small number of numerically estimated parameters. This approach allows for more efficient computation of beta-cell responsivity compared to existing methods with a clear description of uncertainty. We apply this approach to quantify beta-cell dysfunction in a cohort of adolescents with and without CF.

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MS68

First Responder Beta Cells and Herterogeneity in Pancreatic Islet Networks

Insulin-secreting beta cells are functionally heterogeneous. We examined functional architecture of the islets for existence of first responder cells, driving the rest of the islet. Furthermore, we challenged the idea of structural gap-junction-based network being indicative of the functional [Ca2+]-dynamics-based functional network. We used islets isolated from mice that show -cell-specific GCamP6s expression. Islet electrophysiology code was written in C++. The membrane potential for each -cell was related to the sum of individual ion currents as described by the ChaNoma single-cell model. We incorporated coupling current between the beta cells. First responder cells showed characteristics of high membrane excitability and lower electrical coupling to their neighbors. The first-phase response time of -cells in the islet was spatially organized, and consistent up to approximately 24 h. When first responder cells were laser ablated, the first phase [Ca2+] was slowed down and diminished, compared to random cell ablation. Functional networks poorly reflected gap junction structure. Instead, they correlated with the cellular metabolism. In summary, we discover and characterize a distinct first responder -cell state, critical for the islet response to glucose. We also show that previously discovered hub cells do not emerge because of the heterogeneous gap junction coupling in the islet, and instead likely due to heterogeneity in metabolism.

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MS68

A Mathematical Approach to Study Metabolic Oscillations in Beta Cells

Pancreatic β-cells secrete the hormone insulin to maintain the bodys glucose homeostasis. Insulin is released in pulses resulting from periodic bursts of electrical impulses produced by the cells themselves. It has been hypothesized that the ionic current through ATP-sensitive K+ (KATP) channels is responsible for starting and stopping each burst. To assess the role of the KATP channel as a rhythmogenic factor, we suggest monitoring cytosolic ATP/ADP at different glucose concentrations. Our mathematical models show that if oscillations in KATP current are the mechanism driving slow bursting oscillations, then the peaks, nadirs, and average of the ATP/ADP oscillations will be invariant to changes in glucose concentration as long as β-cells are bursting. Conversely, if other factors drive bursting, then the peaks and nadirs of ATP/ADP will change with the glucose level. Data collected using the fluorescent biosensor Perceval-HR to monitor ATP/ADP in mouse islets show the invariance property in the range of glucose concentrations where slow bursting occurs. Fast-slow analysis is employed to demonstrate the ATP/ADP invariance. We show that the critical values corresponding to ATP/ADP peak and nadir levels on the fast subsystem bifurcation diagram are unchanged when we increase glucose in slow bursting. However, if other currents are involved, the invariance is lost since the critical values shift rightward increasing the nadir, peak, and mean ATP/ADP levels.

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MS69

Topological Bifurcations in the Wake Behind An Oscillating Cylinder

The wake of the fluid flow around a circular cylinder typically organizes itself into a set of discrete vortices, the periodic von Krmn vortex street. This is denoted a 2S wake as two Single vortices, one of each sign, are shed during one period. If the cylinder also oscillates, more complex wake patterns may arise. One is the P+S wake, where a Pair and a Single vortex are shed. We will show that the transition from a P to a P+S wake as the amplitude of the cylinder oscillations increases is a complex sequence of topological and dynamical bifurcations and not just a single event as previously assumed. The transition goes through states which have a spatio-temporal structure where vortices are created and destroyed. These states cannot be described by combinations of the simple symbols S and P, and we propose an extended classification scheme to describe these intermediary wakes.

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MS69

Invariant Measures of Walking Droplets in Hydrodynamic Pilot-Wave Theory

We study the long time statistics of a walker in a hydrodynamic pilot-wave system, which is a stochastic Langevin dynamics with an external potential and memory kernel. While prior experiments and numerical simulations have indicated that the system may reach a statistically steady state, its long-time behavior has not been studied rigorously. For a broad class of nonlinearities, we construct the solutions as a dynamics evolving on suitable path spaces. Then, under the assumption that the pilot-wave force is dominated by the potential, we demonstrate that the walker possesses a unique statistical steady state. We conclude by presenting an example of such an invariant measure, as obtained from a numerical simulation of a walker in a harmonic potential.

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MS69

Nonlinear Dynamics, Bifurcations, and Chaos: The Works of Denis Blackmore

Denis Blackmore, a dynamicist and topologist who contributed to a large variety of fields in the sciences, sadly passed away in April 2022. In this talk we will revisit his many contributions to applied dynamical systems. Starting from his early work on the properties of local flows, we will present results from granular mechanics, fluid mechanics, mathematical physics, mathematical biology, and math pedagogy. We hope to provide a glimpse of the incredible breadth of work Denis produced in his long mathematical career.

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MS69

How an Impurity can Produce Regions with Two Effective Temperatures in a Nonlinear Chain

We report on particle dynamics based simulation studies of Toda and Fermi-Pasta-Ulam-Tsingou chains in the presence of an appropriately placed impurity in the chain. Our results suggest that such an impurity potentially splits the chain into two separate regions at different effective temperatures, which remain stable for exceedingly long times. The study suggests that single impurity nonlinear chain based physical systems may have important device applications.

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MS70

Dynamics of Elliptical Vortices with Continuous Profiles

We examine the dynamics of elliptical vortices in 2D ideal fluid using an adaptively refined and remeshed vortex method. Four examples with continuous profiles are considered comprising the compact MMZ and POLY vortices, and noncompact Gaussian and smooth Kirchhoff vortices. The phase portraits in a corotating frame all have two hyperbolic points and two sets of heteroclinic orbits. As the vortices start to rotate, two spiral filaments emerge and form a halo of low-amplitude vorticity around the core; this filamentation is attributed to vorticity advection along the unstable manifolds of the hyperbolic points. In the case of the Gaussian vortex the core rapidly axisymmetrizes, but later on it starts to oscillate and two small lobes enclosing weak vortical fluid form within the halo; this is attributed to a resonance stemming from the core oscillation. In the case of the MMZ, POLY, and smooth Kirchhoff vortices, the core remains elliptical for longer time, and the filaments entrain weak vortical fluid into two large lobes which together with the core form a non-axisymmetric tripole; afterwards however the lobes repeatedly detrain some of their fluid into the halo; the repeated detrainment is attributed to a heteroclinic tangle near the hyperbolic points. While prior work suggested that elliptical vortices could evolve to become either an axisymmetric monopole or a non-axisymmetric tripole, the current results suggest they may oscillate between these states.

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MS70

Vortex Crystal on the Surface of a Curved Torus

As theoretical models of incompressible flows arising in engineering and geophysical problems, vortex dynamics have been considered on surfaces that have various geometric features such as multiply connected domains and spherical surfaces. We here consider the dynamics of point vortices on the surface of a curved torus. Although the flows on the surface of a torus are no longer physical relevance to real fluid flow phenomena, it is of theoretical interest to observe whether the geometric nature of the torus, i.e., a compact, orientable 2D Riemannian manifold with non-constant curvature and one handle, yields different vortex dynamics that are not observed so far. The vortex model is not only an intrinsic theoretical extension in the field of classical fluid mechanics, but it would also be applicable to modern physics such as quantum mechanics and flows of superfluid films. From this application point of view, constructing point vortex equilibria with strengths quantized by 2π is a theoretical challenge. In this talk, we present the equilibrium states of point vortices called vortex crystals, with quantized/non-quantized strengths that are embedded in the background smooth vorticity distributions. We consider two vorticity distributions: a constant vorticity distribution, and a Liouville-type vorticity distribution, where the vorticity consists of the exponential of the stream function and the Gauss curvature of the curved torus.

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MS70

On Boundary Conditions for Vorticity

In many fluid systems, the vorticity (curl of velocity) provides an important field description of the flow, giving insight into structure and dynamics. One challenge with this viewpoint is that the obvious boundary conditions are on velocity, not spatial derivatives of velocity. Historical efforts to formulate mathematical descriptions of boundary conditions on vorticity have focused on individual special cases. Recent studies have succeeded in generalizing conditions for multiple boundary types, but even these efforts are based on the assumption of an incompressible Newtonian fluid. Using a continuum mechanics based approach, we derive boundary conditions on vorticity that decouple fundamental kinematics and dynamics from material properties. This approach simplifies some of the previous analysis, clarifies the physical mechanisms of vorticity generation at boundaries, and facilitates generalization of the vorticity boundary conditions to a broad class of fluid mechanics problems. This work was made possible through support from the Danish Otto Monsted Foundation.

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MS70

A Variational Theory of Aerodynamics

The Euler equation does not possess a unique solution for the flow over a two-dimensional object. This problem has serious repercussions in aerodynamics; it implies that the inviscid aero-hydrodynamic lift force over a two-dimensional object cannot be determined from first principles; a closure condition must be provided. The Kutta condition has been ubiquitously considered for such a closure in the literature, even in cases where it is not applicable (e.g. unsteady). In this talk, I will present a special variational principle that we revived from the history of analytical mechanics: Hertz principle of least curvature. Using this principle, we developed a general (dynamical) closure condition that is, unlike the Kutta condition, derived from first principles. In contrast to the classical theory, the proposed variational theory is not confined to sharp edged airfoils; i.e., it allows, for the first time, theoretical computation of lift over arbitrarily smooth shapes, thereby generalizing the century-old lift theory of Kutta and Zhukovsky. Moreover, the new variational condition reduces to the Kutta condition in the special case of a sharp-edged airfoil, which challenges the widely accepted concept regarding the viscous nature of the Kutta condition. We also generalized this variational principle to Navier-Stokes, thereby discovering the fundamental quantity that Nature minimizes in every incompressible flow.

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MS71

Dynamics on High-Order Networks

Higher-order networks capture the interactions among two or more nodes and they are raising increasing interest in dynamical systems and network theory. Here we show that higher-order interactions are responsible for new dynamical processes that cannot be observed in pairwise networks. We will cover how topology is key to define partial and global synchronization of topological signals, i.e. dynamical signal defined not only on nodes but also on links, triangles and higher-dimensional simplices in simplicial complexes. The Dirac operator is a topological operator can couple the dynamics of topological signals of different dimension leading to Dirac Turing patterns and Dirac synchronization with lead to the spontaneous emergence of a rhythmic phase where the synchronization order parameter displays low frequency oscillations. We will also reveal how triadic interactions, present in ecosystems and neuronal networks, can turn percolation into a fully-fledged dynamical process in which nodes can turn on and off intermittently in a periodic fashion or even chaotically leading to period doubling and a route to chaos of the percolation order parameter. In this framework the giant component of the network becomes a dynamical variable and phase diagram of percolation can be interpreted as an orbit diagram.

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MS71

Global Topological Synchronization on Simplicial and Cell Complexes

Topological signals, i.e., dynamical variables defined on nodes, links, triangles, etc. of higher- order networks, are attracting increasing attention. However the investigation of their collective phenomena is only at its infancy. Here we combine topology and nonlinear dynamics to determine the conditions for global synchronization of topological signals on simplicial and cell complexes. On simplicial complexes we show that topological obstruction impedes odd dimensional signals to globally synchronize. On the other hand, we show that cell complexes can overcome topological obstruction and in some structures, signals of any dimension can achieve global synchronization.

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MS71

Phase Reduction Analysis of Collective Dynamics in Systems of Coupled Oscillators with Higher-Order Interactions

We consider a system of coupled limit-cycle oscillators with higher-order interactions and derive the reduced coupled phase equations by using the phase reduction theory. In contrast to pairwise interactions, the reduced phase equations generally possess phase coupling functions that depend on two or more phase differences between the oscillators. For coupled Stuart-Landau oscillators with 3-body interactions, we can analytically derive the higher-order phase coupling functions, which possess not only the simplest 3-body attractive sinusoidal coupling but also non-sinusoidal coupling terms reflecting the shapes of the isochrons. We analyze the effect of these non-sinusoidal terms on the collective dynamics of the system theoretically and numerically.

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MS72

A Posteriori Validation of Generalized Polynomial Chaos Expansions for Random Invariant Sets

Generalized polynomial chaos (gPC) expansions are a powerful tool to study differential equations with random coefficients, allowing in particular to efficiently approximate random invariant sets associated to such equations. However, in practice gPC also introduce an extra level of uncertainty, as we can only work with truncated expansions. In this talk, we use ideas from validated numerics in order to obtain rigorous a posteriori error estimates regarding truncated gPC expansions, together with existence results about exact gPC expansions of random invariant sets. This approach also provides a new framework for conducting validated continuation, i.e. for rigorously computing isolated branches of solutions in parameter-dependent systems, which generalizes in a straightforward way to multi-parameter continuation.

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MS72

Random Switching Near Bifurcations

Random switching between deterministic vector fields has been used to model a large variety of phenomena, ranging from gene expression to ecosystems with seasonal fluctuations. Often, all of the vector fields involved belong to a specific class (e.g., the class of Lotka-Volterra vector fields) and only differ in the values assigned to the parameters. Since bifurcations occur generically in parametric families of vector fields, it is then important to understand the effect of random switching between parameter values taken from the vicinity of a bifurcation point. In this talk, we focus on qualitative and quantitative properties of the invariant probability measures arising from Markovian switching dynamics near fold, Hopf, transcritical, and pitchfork bifurcations. For different switching rates, we study the number of ergodic invariant probability measures and whether these measures admit a smooth density. We also examine under which conditions finite-time blow-ups occur. The talk is based on the eponymous paper with Christian Kuehn.

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MS72

Global Sensitivity Analysis in High-Dimensional Parameter Spaces

In complex system modeling and data assimilation, parameter identifiability is a central problem in calibrating model accuracy, extracting concise information from data, guiding experimental design and predictions. Identifiability is tied to sensitivity of model output with respect to perturbations in inputs. Besides one-at-a-time local analysis of single variables, it is of great interest to study the global parameter domain and incorporate interactions among variables. Monte-Carlo simulations are most commonly applied in engineering fields to approximate desired statistics. However, the cost of simulations are constrained by both the model complexity and the so-called curse of dimensionality - an exponential dependence of computational cost with respect to number of parameters. We propose to take a meta-modeling approach by replacing a physical model with a flexible function approximator (in our case, polynomial chaos expansion) that provides best fit on a relatively small set of data, and obtain estimated statistics directly. We demonstrate that the dimensionality issue is mitigated by reframing the analysis as a polynomial regression problem, and apply low-rank functional tensor networks as an efficient meta-model and reduce computational cost. Results are discussed for a high-dimensional battery model and the generalized Lotka-Volterra biological model.

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MS73

Non-Smooth Tipping in the Stommel Model of Atlantic Thermohaline Circulation

In this talk we will look at the behaviour at tipping points close to non-smooth fold bifurcations in one-dimensional oscillatory forced systems. The focus is the Stommel-Box, and related climate models, which are piecewise-smooth continuous dynamical systems, modelling thermohaline circulation. These exhibit non-smooth fold bifurcations which arise when a saddle-point and a focus meet at a border collision bifurcation. By using techniques from the theory of non-smooth dynamical systems we are able to provide precise estimates for the general tipping behaviour at the non-smooth fold as parameters vary. These are significantly different from the usual tipping point estimates, showing a much more rapid rate of tipping. We also see very rapid, and non-monotone, changes in the tipping points due to the effect of non-smoothness in the system. All of this has important implications for the prediction of tipping in climate systems

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MS73

A Simple Mechanism for Stable Oscillations in Large-Scale Ocean Circulation

The global ocean circulation plays a pivotal role in the regulation of the Earth's climate, as well as carbon and nutrient cycles and the habitability of the oceans for marine life. Transitions in circulation patterns are known to have occurred in the past and, considering their global importance, it is crucial to understand the nature and drivers of such transitions. Here we present stable oscillations observed in the ocean circulation of an Earth System Model of intermediate complexity. The presence of the oscillations depends on a circumpolar current. We adapt a simple ocean box model to include a delayed feedback to represent a circumpolar current and investigate stable oscillatory solutions by bifurcation analysis. Our results provide insight into oscillations observed in simulations based on land mass configurations typifying the geological past and also highlight the potential influence of changing circumpolar current speed on the stability of the ocean's meridional overturning circulation.

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MS73

Analysis of a Conceptual Model for the Atlantic Meridional Overturning Circulation with Two Time Delays

We study a scalar delay differential equation (DDE) model with two time delays for the Atlantic Meridional Overturning Circulation (AMOC). Here, the time delays are associated with the temperature feedback between North Pole and Equator and the salinity exchange between surface and deep water at the Pole. We perform a numerical bifurcation analysis of the DDE with the continuation package DDE-Biftool. It reveals rich behavior of this AMOC model organized by homoclinic orbits, as well as resonance phenomena due to the interplay between the two delayed feedback loops

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MS74

Theory and Computation of the Spectral Properties of Pullback Operators in Dynamical Systems

Koopman operator methods along with the associated numerical algorithms have provided a powerful methodology for the data-driven study of nonlinear dynamical systems. In this talk, we will give a brief outline of how the Koopman group of operators can be generalized beyond function spaces to the space of sections of various vector bundles over the state space. We describe their relationship with the standard Koopman operator on functions as well as describe the new spectral invariants produced by these generalized operators. We then demonstrate how the recently developed spectral exterior calculus framework can be utilized to compute the spectral properties of the generator of the induced operator on sections of the cotangent bundle. We conclude with some applications of the algorithm to some well-known dynamical systems.

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MS74

Input-Parameterized Koopman Eigenfunctions

The Koopman operator is a linear operator which gives the evolution of observables under the action of a nonlinear dynamical system. This operator is infinite dimensional, but it admits a finite-dimensional linear representation for systems with a point spectrum. In the control of systems with multiple fixed points, one can use piecewise control methods and local Koopman models. We propose a nonlinear Koopman representation that is accurate globally and enables a finite dimensional model and the application to control problems. This representation uses input parameterized eigenfunctions. We illustrate this on the control between the basins of attraction of the Duffing oscillator with dissipation.

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MS74

Subspace Invariance Properties of Mixed Dictionary Functions for Approximating Koopman Operators

Koopman operators model nonlinear dynamics as a linear dynamic system acting on a nonlinear function as the state. This nonstandard state is often called a Koopman observable and is usually approximated numerically by a superposition of functions drawn from a dictionary. In a widely used algorithm, Extended Dynamic Mode Decomposition, the dictionary functions are drawn from a fixed class of functions. Recently, deep learning combined with EDMD has been used to learn novel dictionary functions in an algorithm called deep dynamic mode decomposition (deepDMD). The learned representation both (1) accurately models and (2) scales well with the dimension of the original nonlinear system. We discover that structured mixing of heterogeneous dictionary functions drawn from different classes of nonlinear functions achieve the same accuracy and dimensional scaling as the deep-learning-based deepDMD algorithm. We specifically show this by building a heterogeneous dictionary comprised of conjunctive logistic and conjunctive radial basis functions. We show this mixed dictionary to satisfy subspace invariance properties and then demonstrate its ability in simulations. This mixed dictionary achieves the same accuracy and dimensional scaling as deepDMD with an order of magnitude reduction in parameters, while maintaining geometric interpretability. These results strengthen the viability of dictionary-based Koopman models to solving high-dimensional nonlinear learning problems.

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MS74

Learning Koopman Evolution Groups with the Spectral Exterior Calculus

We present a data-driven, exterior calculus framework for learning dynamical systems on low-dimensional manifolds, based on representations of vector fields in frames (i.e. overcomplete bases) for Sobolev spaces. Using the eigenvalues and eigenfunctions of the Laplacian of functions, we parameterize and represent vector fields as linear combinations of frame elements, which in turn act as generators of Koopman evolution groups. We present an implementation of our framework that consistently represents vector fields using Monte Carlo approximation from data sampled on manifolds. In addition, we solve initial-value prediction problems using our vector field representations and compare the performance with solutions under the true system.

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MS75

Pattern Formation in Four-Component Reaction-Diffusion Systems

This study is to investigate what can be learned about cell polarisation from various experimental models of activator-inhibitor type that have been proposed in the literature. These models typically have two activator and two inhibitor fields. Our study investigates polarisation models of cells within two distinct regimes, in which the amount of protein is either conserved or not conserved. In the non-conservative regime, two types of patterns are obtained; interleaved and overlaid. The temporal stability analysis shows that the localised patterns created in the interleaved case are stable. Compared to the overlaid pattern, the localised patterns are unstable and evolve into the interleaved one. Passing to the mass conservation limit also suggests a novel mechanism for creation heteroclinic states.

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MS75

The Roles of Front Instabilities in Reversing Species Invasion and Desertification

Invasion and desertification fronts represent two crucial ecological processes in ecosystem degradation that involve loss of biodiversity and ecosystem functioning and call for the study of ecosystem-recovery mechanisms. To this end, we study front instabilities in two reaction-diffusion models. Invasion is modeled by an extended Lokta-Volterra model for a native and an invasive plant species, where the presence of pathogens mediates the competition between them. For pathogens with an Allee effect, we identify a bistability range of counter-propagative fronts representing invasion and recovery dynamics. The two fronts differ in their pathogens levels at the narrow front zone. This result suggests ecosystem-recovery practices based on manipulating the pathogen level in the front zone. Desertification is studied using a model for dryland vegetation comprising equations for the vegetation biomass and the soil-water content. Earlier studies suggested that ecosystem recovery can be achieved through a transverse instability of a desertification front that grows vegetation fingers back into degraded areas. Based on the derivation of amplitude equations and a geometrical singular-perturbation approach, these studies provided insufficient information about the biotic and abiotic factors that control the instability threshold. Using a semi-analytical study, we uncover these factors and use our findings to delineate possible practices for reversing desertification.

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MS75

Organization of Spatially Localized States Near a Codimension 3 Cusp-Turing Bifurcation

The transition from standard homoclinic snaking to foliated snaking of spatially localized structures in driven dissipative pattern-forming systems is described by a generic partial differential equation valid near a cusp-Turing bifurcation. This equation is analyzed using a combination of analytical and numerical continuation techniques. The results are illustrated using the Lugiato-Lefever equation of nonlinear optics and different models of dryland vegetation cover.

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MS76

Coarse-Graining of Stochastic Systems

Coarse-graining or model reduction of dynamical systems is a modelling tool used to extend the time-scale of simulations in a range of fields. When applied in molecular dynamics with moderate times-cale separations, standard coarse-graining approaches seek to approximate the potential of mean force, which is the expected potential energy conditioned on the value of the coarse-grained variables, and use this to drive an effective Markovian model. Here, in an overdamped setting, the simple case of a quadratic energy is studied. It is shown that while the standard recipe for model reduction accurately captures equilibrium statistics, it is possible to derive an easy-to-implement Markovian approach to better capture dynamical statistics such as the mean-squared displacement. Both analytical and numerical evidence for the efficacy of the new approach is provided. This is a joint work with Dr. Thomas Hudson from University of Warwick, UK

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MS76

Regression-Based Projection for Learning MoriZwanzig Operators

More than half a century ago, Mori and Zwanzig (MZ) developed a mathematically rigorous formalism for constructing reduced-order models for dynamical systems using functional projection operators. Several recent studies have established that with Mori's linear projection operator, it is possible to adopt a data-driven approach to learn the MZ operators using the time series of the resolved dynamics. In this talk, I will present our latest proposition of using regression analysis to define the projection operators, and a data-driven method for learning the associated MZ operators using time-series data. The newly proposed method can be considered as a generalization of our recently proposed method (Lin et al. 2021, SIADS) because it is not restricted to linear regressions. As we gradationally increased the complexity of the regression models, we observed a consistent improvement of the learned reduced-order models on a few test examples. We still observed considerable improvements by including the MZ memory effect in these nonlinear projections, justifying the necessity of accounting for the past histories of under-resolved systems. We believe that the proposed method for learning MZ operators is promising because it is applicable to most data-driven methods (e.g., approximate Koopman and SINDy) for learning dynamical systems.

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MS76

An Efficient, Data-Informed Coarse-Graining Model for Cortex

Neuronal circuitry in the cerebral cortex are characterized by a high degree of structural and dynamical complexity, and this biological reality is reflected in the large number of parameters and runtime cost of cortical models. This inherent complexity poses many challenges for modelers, including but not limited to constraining model parameters and scaling up models to study phenomena involving larger cortical networks. In this talk, I will report on a recently proposed approach to address these challenges based on a class of parsimonious data-informed models. I will show that the approach efficiently predicts spontaneous activity in the primate primary visual cortex, thereby helping to constrain cortical model parameters. Time permitting, I will also discuss how the approach can be extended to study visual cortex under drive.

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MS76

Data Driven Nonlinear Model Reduction for Stiff Stochastic Dynamical Systems

Model reduction for high-dimensional stochastic systems is fundamental for understanding, efficiently simulating, predicting and controlling the behavior of complex systems and models arising across the sciences, including Physics, Biology, Physical Chemistry, Atmospheric Science, Economics. These stochastic model frameworks are notably hard to analyze analytically and to simulate numerically, due to the curse of dimensionality and the notorious stiffness of the system. One commonly used reduced model is to map the dynamics onto a relatively low-dimensional manifold that is sufficient to capture the dynamics at the slow timescales. From our previous work on ATLAS algorithm, we can efficiently estimate a low-dimensional, nonlinear manifold, and the effective dynamics on well-distributed landmarks. We will use the framework of physics informed neural networks to build a global simulator for the reduced model. We will test many large-time and large-space dynamical quantities of interest, such as rare transition rate between metastable states and mean first passage time of each metastable state in various examples.

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MS77

Bifurcation Analysis of Twisted States on Networks of Kuramoto Oscillators

The Kuramoto model provides a prototypical framework to study the dynamics interacting particle systems. The classical heterogeneous Kuramoto model exhibits two main dynamically important states - desynchronization and partial synchronization. Depending on the parameters of the system, the long term behavior always tends to either of these states. However, when considering identical oscillators on a nearest-neighbor graph, the Kuramoto model exhibits more interesting states such as uniformly twisted states. It was discovered by Wiley, Strogatz and Girvan in 2006 that the stability of these twisted stated depends on the coupling range of the nearest-neighbor graph. Since this original analysis was published, many generalizations and variants were developed. In this talk, we will analyze the bifurcation in which these twisted states lose their stability upon varying parameters, such as the coupling range, of the system. We investigate the existence and shape of bifurcating equilibria in the infinite particle limit.

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MS77

Complex Dynamics in Adaptive Networks of Phase Oscillators

Networks of coupled dynamical units give rise to fascinating collective dynamics such as the synchronization of oscillators/neurons. Adaptive network dynamics describes the interplay between dynamics on and of the network which adds an additional layer of complexity: the collective node dynamics influence the dynamics of the network and vice versa. We study a model of Kuramoto phase oscillators with a general adaptive learning rule with three parameters that includes as special cases both (anti-)Hebbian learning and spike time dependent plasticity. An important feature is a parameter allowing to perturb off the non-adaptive manifold with stationary coupling to study the impact of adaptation on the collective dynamics. We carry out a detailed bifurcation analysis for N=2 oscillators bidirectionally asymmetric coupling and provide stability diagrams. We find that adaptation dynamics (in terms of nontrivial bifurcations) arises only when the learning strength exceeds a critical threshold. While aforementioned special cases for the learning rule yield non-trivial multistability and bifurcation scenarios, our analysis reveals that mixed-type learning rules yield far more complicated and rich dynamics such as a transition to chaotic dynamics. We numerically investigate large systems with N=50 oscillators and investigate which of our findings carry over from the case of N=2 oscillators.

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A Tutorial on Kuramoto Networks with Pathological Behavior

Trees synchronize, while rings might not. Adding an edge to a tree might destroy synchronization, while adding one to a ring might force it. In recent years, a great effort has been put into understanding the relation between the equilibria in Kuramoto networks and the properties of the underlying graph. We discuss how to design graphs with unusual behavior and how to analyze them. For example, we construct Eulerian graphs with all-zero-eigenvalue equilibria, and connected planar graphs with infinitely many stable equilibria. In general, we show how a bottleneck can effectively disconnect a connected network, leading to manifolds of stable equilibria of arbitrarily large dimension. These pathological examples, for which linear stability analysis does not apply, are treated with combinatorics and topological bifurcation theory.

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MS77

Mean Field Limits of Heterogeneous Networks

Many science phenomena are modelled as interacting particle systems (IPS) coupled on static networks. In reality, network connections are far more dynamic. Connections among individuals receive feedback from nearby individuals and make changes to better adapt to the world. Hence, it is reasonable to model myriad real-world phenomena as co-evolutionary (or adaptive) networks. In this talk, I will briefly introduce our recent work on mean field limits of coevolutionary Kuramoto networks which incorporate heterogeneity.

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MS78

Reconstruction of Long-Term Dynamics from Data?

The importance that dynamical systems theory in general places on invariant sets and long-term behaviour needs sometimes to be reconciled with the inherent finiteness of data. This talk considers questions of reconstruction of dynamical systems from minimal data, building on the reservoir computing paradigm which is currently of substantial interest due in part to its attractive mathematical formulation and the Echo State Network (ESN) idea. We apply the ESN formalism to data generated from a known dynamical system and ask to what extent the ESN is able to (i) reconstruct the original dynamics, or, more demandingly, (ii) estimate the parameters of a dynamical system diffeomorphic to the original, and by implication allow estimation of the attractors of the original system.

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MS78

Symmetric Homoclinic Tangles in Reversible Dynamical Systems have Positive Topological Entropy

We consider reversible vector fields in $\mathbb{R}^{2n}$ such that the set of fixed points of the involutory reversing symmetry is n-dimensional. Let such system have a smooth one-parameter family of symmetric periodic orbits which is of saddle type in normal directions. We establish that topological entropy is positive when the stable and unstable manifolds of this family of periodic orbits have a strongly-transverse intersection.

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MS78

Periodic Perturbation of Cyclic Dynamics

We discuss the outcome of periodic perturbations of attracting cyclic dynamics. The system to be perturbed may be either a periodic orbit, a heteroclinic cycle or a flow-invariant torus. The analysis consists in reducing to discrete-time dynamics on a cylinder. Some of the results are joint work with Alexandre Rodrigues (CMUP and ISEG, Portugal).

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MS78

Stability of Heteroclinic Cycles in Ring 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: mean residence times near the fixed points in the cycle are undefined, and there is a persistent slowing down. We examine ring networks with nearest-neighbour or nearest-m-neighbour coupling, and show that there exist classes of heteroclinic cycles in the phase space of the dynamics. We show that there is always at least one heteroclinic cycle which can be asymptotically stable, and thus the attracting dynamics of the network are expected to be non-ergodic. We conjecture that much of this behaviour persists in less structured networks and as such, non-ergodic behaviour is somehow typical.

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MS79

Modeling Techniques for Clinical Time Series: Lessons Learned the Hard Way

This presentation will explore healthcare-specific applications of artificial intelligence (AI) with clinical time series, highlighting various challenges and insights gained. The projects include predicting diabetes in infants before birth, extracting heart rate variability from magnetoencephalography data, and approximating vascular stiffness. In each of these cases, we use high-resolution (and real-time) data as inputs to statistical machine learning, or deep learning models. In our first example with a small sample size, (n=90 mothers), we employ transfer learning on a pretrained deep learning model to assign probabilities of hypoglycemia to neonates using maternal continuous glucose monitoring (CGM). In this example, we will show a low-code example of transfer learning with pretrained AI models. Next, we measure the minute fluctuations in the magnetic field caused by firing neuron bundles via Magnetoencephalography (MEG) to approximate heart rate variability metrics. We will show how we repurposed and adapted freely available AI models to generate new insights. Finally, we use the time interval between a heart contraction (R-peak on an Electrocardiogram) and corresponding rise on a blood pressure to calculate the speed of each pulse, a surrogate measure of vascular stiffness. Through this example, we demonstrate the importance of carefully selecting Python packages and the utility of structured development.

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Variability in the Arterial Blood Pressure Waveform and Its Effects on Patients with Spontaneous Intracerebral Hemorrhage

Intracerebral hemorrhage (ICH) is a severe form of stroke marked by bleeding into the brain parenchyma. Approximately 40% of ICH patients die within 30 days, and over 70% never return to baseline functional ability. While absolute blood pressure control in acute and post-acute period remains important, blood pressure variability has emerged as a stronger predictor of patient outcomes. Systolic blood pressure variability (SBPV) may be influenced by several factors, including biology of vasculature, ICH characteristics, comorbidities, treatments and medications, and external stimuli. However, SBPV in real-time clinical settings is not well characterized. In this talk, we will detail current approaches to assessing SBPV and modelling for ICH patients. We will further discuss advancements in assessing dynamic arterial blood pressure waveforms collected during the acute hospitalization, demonstrating the multi-factorial associations between patient characteristics, treatment modalities and SBPV, and how these contribute to patient outcomes.

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MS79

Modeling the Interplay Between Blood Flow and Oxygen Transport in the Defective Heart

This talk will describe a physics-based computer modeling framework for calculating time-dependent blood and oxygen dynamics in humans. The framework is based on a compartmental description for different regions of the circulation. This approach will be applied to study several congenital heart defects in which mixing of oxygenated and deoxygenated blood occurs via a surgical connection. The size of the connection will be explicitly described as part of the model. Several computer simulation studies will be presented to highlight the utility of the model in suggesting ways to optimize surgical interventions for these defects.

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MS79

Optimizing Hemodynamic Targets for Functional Cerebral Blood Flow Control in Critical Illness

Changes in cerebral autoregulation of blood flow during sepsis may play a critical role in the high morbidity and mortality among patients with sepsis-associated brain dysfunction (i.e., encephalopathy, delirium). Sepsis guidelines recommend mean arterial pressure of greater than 65 mmHg for adequate organ perfusion. Bedside assessment of cerebral autoregulation using moving continuous correlation coefficients between high-frequency time-synchronized signals of near-infrared spectroscopy brain monitoring and arterial pressure may help individualize hemodynamic targets that optimize blood flow in the brain. We strive to determine whether decreased blood flow defined by individualized autoregulation-guided targets is associated with increased incidence and severity of sepsis-associated encephalopathy compared to that defined by standard thresholds. We use data-driven approaches to identify risk factors for differences between empiric targets and therapeutic targets tailored to autoregulation and explore high frequency variables that affect optimal mean arterial pressure and autoregulatory limits. Trends in how specific variables affect optimal mean arterial pressure help individualize targets and are providing the necessary data to design and power a future randomized trial to evaluate the effect of individualizing therapy. Personalized goals based on cerebral autoregulation monitoring may decrease the impact of sepsis-associated encephalopathy and improve outcome from sepsis.

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MS80

Filtered Finite State Projection Method for the Analysis and Estimation of Stochastic Biochemical Reaction Networks

Recent advances in fluorescence technologies and microscopy techniques have significantly improved scientists ability to investigate biological processes at the single-cell level. However, fluorescent reporters can only track the temporal dynamics of a limited number of critical components in a cell (e.g. fluorescent proteins), leaving other pivotal dynamic components (such as gene state) hidden. Moreover, the interactions among intracellular biomolecular species are inevitably stochastic in the low copy number regime. Therefore developing mathematical and computational tools for analysing the behaviour of stochastic reaction networks from time-course data is urgently needed. Here we develop a finite-dimensional filter for estimating the conditional distribution of the hidden (unobserved) species given continuous-time and noise-free observations of some species. In this setting, the conditional distribution evolves in time according to a large or potentially infinite-dimensional system of coupled ordinary differential equations with jumps, known as the filtering equation. We develop a Finite-State Projection method, which provides an approximated solution by truncating the infinite-dimensional system. Additionally, we give computable error bounds to the algorithm. Finally, we present several numerical examples to illustrate our method and compare its performance with an existing particle filtering method for estimating the conditional distribution.

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MS80

Frequency Domain Approaches for the Analysis of Stochastic Reaction Networks

Biomolecular reaction networks serve as accurate mathematical representations of intracellular processes. In cases where the constituent species have low molecular counts, the dynamics of such networks are stochastic and commonly modeled as continuous-time Markov chains (CTMCs). Computational analyses and inference of such stochastic models are fraught with many difficulties, arising mainly due to an inherent curse of dimensionality which causes the underlying state-space to be exorbitantly large or even infinite. While some of these issues can be mitigated by efficiently simulating CTMC trajectories and designing suitable Monte Carlo procedures, these approaches generally impose a heavy computational burden as they often require a large sample of trajectories to achieve the desired statistical accuracy. The aim of this talk is to present novel frequency domain methods for efficient computational analyses of stochastic reaction networks. We shall show that these methods typically require only a handful of simulated trajectories for obtaining statistically reliable estimates of the frequency spectrum of various time-varying quantities of interest (like means, variances, autocorrelation etc.). Several examples will be presented to illustrate these frequency domain methods for applications like estimation of moment-trajectories, design of biomolecular controllers, optimization of synthetic oscillator devices, and studying cell-cycle effects on intracellular processes.

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MS80

Reaction Networks in Random Environment with Applications to Epidemics and Genetics

In many problems of mathematical biosciences the issue of a heterogeneous environment is an important feature of the mathematical model. In this talk, I will provide some examples of the usage of non-homogenous Markov intensity functions in both macro systems in ecology or epidemiology and micro systems in genomics and cellular biology. From the viewpoint of the theory of stochastic chemical reaction networks such intensity functions may be viewed as defining martingale problems for a class of counting processes that may be represented is a particularly simple form. I will show how such processes may be used to construct more realistic stochastic models of multi-scale biological systems.

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MS80

Bayesian Approach for Modelling RNA Velocity

RNA velocity is a paradigm to interpret cellular differentiation, exploiting the evolution of gene expression of cells at different stages of maturity during the evolution path. Gene expression is regulated through the fundamental processes of transcription, splicing and degradation, which can be modelled as a stochastic chemical reaction network, whose rate constants need to be estimated from experimental data collected by single-cell RNA sequencing. The development process among the cells is triggered by the switch of some genes, which is modelled through a binary modification of the gene-specific transcription rates. The principal method that is use in RNA velocity to estimate models parameters is scVelo (Bergen V. et al, Generalizing RNA velocity to transient cell states through dynamical modeling, Nature biotechnology, 2020). This approach has already been criticized over various aspects and we also show that, starting from simulated data, it is not able to recover the underlying parameters that describe the transcription dynamic. We propose a model that is simplified, but also mathematically better founded and that, differently from scVelo, ensures the identifiability of the parameters. Among the fundamental differences with Bergens approach, we have the substantial absence of artificial preprocessing steps, we make use of a data distribution that is motivated by reaction network theory and assume that the cells of the same type follow common dynamics.

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MS81

A Matter of Timing - An Investigation of the Interplay Between Reproductive Hormones and Ovarian Follicles

The menstrual cycle describes changes in hormone concentrations at different time scales and, subsequently, the maturation of ovarian follicles, the preparation of the uterus for a possible pregnancy, and menstruation. Its regulation is enabled through feedback loops of hormones secreted by the glands forming the hypothalamic-pituitary-gonadal axis (HPG axis). Established knowledge about the regulation of the menstrual cycle exists; however, we lack an in-depth understanding of individual alterations in the hormone secretion pattern and effects of hormonal treatments, such as Controlled Ovarian Stimulation (COS). Here, we present a mechanistic model of the menstrual cycle. Formulated as a system of non-linear ordinary differential equations, the model covers the growth of ovarian follicles initiated at random time points and the dynamics of hormones along the HPG axis throughout consecutive cycles. In our simulations, ovarian follicles grow in waves. This emergent phenomenon supports the hypothesis of human ovarian follicle growth in waves. In addition, we demonstrate the models applicability to simulate, compare and potentially optimize treatment protocols for COS. Overall, our model provides a modelling and simulation framework to study various aspects of the menstrual cycle and could become an integral part of clinical decision-support systems in reproductive endocrinology.

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MS81

GnRH Hormone Release Regulation as Dictated by Kisspeptin and Autocrine Feedback

Pulsatile release of gonadotropin-releasing hormone (GnRH) from hypothalamic GnRH neurons is a crucial for reproductive health. Previous studies have shown that these neurons exhibit various rhythms occurring at different times scales ranging from seconds (electrical activities) to hours (GnRH pulsatility). How these rhythms communicate with each other to drive hormone release remains incompletely understood. We previously developed a Hodgkin-Huxley type model to explain how membrane voltage of these neurons exhibit two modes of burst firing: parabolic and irregular bursting. This work was then extended by coupling electrical activities of GnRH neurons to hormone release, making two key assumptions about the model: GnRH neurons express GnRH receptors that allow for autocrine feedback, and GnRH neurons respond to pulsatile kisspeptin through GPR54 receptors. The model was used to explore how the different rhythms in GnRH neurons interact collectively to produce pulsatility. Our results revealed that electrical activity, autocrine feedback and kisspeptin stimulation must act in synergy to produce such pulsatility. It also showed that kisspeptin acts as a global signal while autocrine feedback acts as a local signal to drive GnRH release, with approximately 7-1 locking between them, and that electrical activity controls baseline release as well as rare release events. In this talk, we will give an overview of these results and their implications.

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MS81

Heterogeneous Population Spiking Dynamics and Secretory Signal Processing in Vasopressin Neurons

Hormone secreting vasopressin neurons of the brains hypothalamus form part of the homeostatic brain/body systems that maintain osmotic pressure (salt/water balance). In response to synaptic input signals encoding osmotic pressure and changes in plasma volume, they generate spikes (action potentials) which trigger their secretory terminals in the posterior pituitary gland. The thousands of neurons secretory signals sum together to generate a blood plasma vasopressin signal that acts at the kidneys to control water loss. These neurons are distinctive for their phasic patterned spiking, consisting of long bursts and silences lasting tens of seconds. However, they are also highly heterogeneous in their activity levels and patterning, and this heterogeneity changes dynamically both with acute and chronic stimulation. In normal conditions, many are slow firing or only show simple patterned continuous spiking. After prolonged osmotic stimulation many more shift into the phasic patterning. Here we use a coupled spiking and secretion model fitted to multiple in vivo recordings of these neurons in varied physiological states to investigate what combination of activity-dependent changes to their intrinsic properties and input signals might explain these changes in patterning. We then use the coupled models as a heterogeneous population to simulate the summed plasma signal and predict how the dynamic patterning properties relate to functional signal processing.

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MS82

Strategies for Multi-Season Eradication of the Coffee Berry Borer

The coffee berry borer (CBB) is worldwide the most serious insect pest of coffee. Understanding and controlling the dynamics of its reproduction is essential for pest management. A mathematical model of the infestation progress of the coffee berry by the CBB during several coffee seasons is formulated. The model represents the interaction among five populations: uninfested, slightly infested, and severely infested coffee berries, and free and encapsulated CBBs. A one-dimensional map is derived for tracking the population dynamics subject to certain coffee harvesting percentages over several seasons. Stability analysis of the maps fixed points shows that CBB infestation could be eliminated or controlled to a specific level over multiple seasons of coffee harvesting. However, the percent of coffee harvesting required for eradication is determined by the level of CBB infestation at the beginning of the first season and in some cases it is impossible to achieve that percentage.

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MS82

The Interplay Between Metastability, Neural Networks, and Pathology

A large amount of research suggests that the neural code can be represented by metastable state transitions. That is, computation occurs by the switching of stable patterns of neural activity due to various forms of perturbation. Past works indicate that the mathematical behavior underlying biological and artificial recurrent neural networks (RNNs) are topologically similar when both structures are trained to perform identical tasks, and furthermore, do not depend heavily on the cellular level architecture of the network. As such, conclusions may be drawn about the underlying dynamics of biological networks by analyzing their artificial counterparts. However, little is understood about what dynamical features they can express and how these features can be used to enact desired computations. We explore these two areas in this talk, beginning by analyzing recurrent neural networks through the lens of continuous time dynamical systems. Through this medium, we showcase many of the expressible dynamics of RNNs crucial for known neural computation and highlight instances where desired dynamics may be unobtainable. We then analyze how RNNs use their dynamical features to enact various temporal computations, focusing primarily on nonlinear working memory tasks. Furthermore, we discuss how neurological disease arises in this dynamical systems framework.

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MS82

Delayed Hopf Bifurcation and Control of a Ferrofluid Droplet with a Time-Varying Magnetic Field

In our previous work, we designed a crossed magnetic field with both radial and azimuthal components that deform a confined ferrofluid droplet in Hele-Shaw cell into a stably spinning "gear" via a traveling wave along the droplet's interface. Weakly nonlinear analysis with a finite number of harmonic modes was used to predict the evolution. With the azimuthal field's strength fixed, we now show that the traveling wave solution bifurcates from the trivial solution, as the radial field's strength increases. A center manifold reduction reveals the geometrical equivalence between a two-harmonic-mode coupled ODE system and the Hopf bifurcation. The resulting amplitude equation captures the evolution of the droplet's interface, and the radius of the limit cycle reveals the leading mode's amplitude. Next, inspired by the well-known delay behavior of time-dependent Hopf bifurcations, we design a slowly time-varying magnetic field that can control the timing of the emergence of the targeted spinning "gear" shape. To capture these dynamics, a time-dependent Landau equation is derived from a multiple-time-scale expansion.

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MS83

A Dynamical System of Vortex Reconnection for a Finite-Time Singularity of the Navier-Stokes Equations

Vortex reconnection has been studied intensively as a fundamental process both in classical and quantum turbulence. In collaboration with Keith Moffatt (Cambridge) and Phil Morrison (Austin), the author has been investigating this problem as the problem of a finite-time singularity of the Navier-Stokes equations. In this talk, we will first review the recent developments of the singularity/regularity studies in the theoretical and computational approaches, and then we will present a dynamical system which analytically describes the evolution of vortex reconnection towards a finite-time singularity of the Navier-Stokes equations. In the dynamical system, we placed two tilted circular vortex rings of circulation $\pm\Gamma$ and radius R, symmetrically on two planes at angles $\pm\alpha$ to a plane of symmetry. It is shown that the behavior near the points of closest approach of the vortices (tipping points) is determined solely by the curvature κ at the tipping points and by the half of the minimum distance, s and the core radius, δ. The Biot-Savart law is used to obtain analytical expressions for the rate of change of these three variables, and a nonlinear dynamical system relating them is obtained.

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MS83

Liouville Chain Solutions of the Euler Equation

We describe a large class of solutions of the two-dimensional steady incompressible Euler equation in which point vortices are embedded in a non-constant background vorticity field such that the whole arrangement is stationary. This background vorticity is proportional to the exponential of the stream function and leads to a Liouville-type partial differential equation. We exploit the known solution structure of a class of solutions of this Liouville-type equation to construct solutions, which we call Liouville chains, of the Euler equation mentioned above. Liouville chains can be constructed as iterated solutions starting from a simple purely point vortex equilibrium (without a background field). Each iteration forms one link in the chain and can terminate after one step, a finite number of steps, or go on indefinitely. The solutions are given in terms of an arbitrary positive real parameter, and as this parameter goes to zero or infinity, we find that the background vorticity concentrates into point vortices, and in the limit the solutions go over into purely point vortex equilibria. The solutions also contain arbitrary complex-valued parameters which arise as integration constants in the iteration. We describe several examples illustrating all these properties.

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MS83

Dynamics of Coaxial Arrays of Vortex Rings

It is well known that a spatially-periodic array of coaxial thin-cored vortex rings moves uniformly without change of shape in the direction of the central axis of symmetry, and is an equilibrium solution of Euler's equations. We revisit this classical result, originally due to Vasilev (1916), using the modern formalism of Borisov et. al (2013). In a frame of reference moving with the system of vortex rings, the motion of passive fluid particles is investigated as a function of the two nondimensional parameters that define this system: $\varepsilon = a/R$, the ratio of minor radius to major radius of the torus-shaped vortex rings, and $\lambda = L/R$, the separation of the vortex rings normalized by their radii. Three distinct streamline topologies are found, separated by two bifurcation curves in $\epsilon - \lambda$ space. Analogous to the case of an isolated vortex ring, the atmospheres can be 'thin-bodied' or 'thick-bodied'. Additionally, we find the occurrence of a 'connected' system, in which the atmospheres of neighboring rings touch at an invariant circle of fluid particles that is stationary in a frame of reference moving with the vortex rings. Preliminary investigations of the motion of two interacting coaxial vortex ring arrays are also carried out, which is one of the last unsolved integrable problems in vortex dynamics.

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MS83

On Linear Stability of Inviscid Vortices

We consider the problem of determining the linear stability of inviscid vortices such as vortex patches in 2D and axisymmetric vortex rings in 3D. These vortices are equilibrium solutions to free-boundary problems based on the Euler equations and their stability analysis is performed using recently-developed methods of shape differentiation applied to the contour-dynamics formulation of the problem. This approach allows us to systematically account for the effect of boundary deformations on the linearized evolution of the vortex. Stability properties are then determined by the spectrum of a singular integro-differential operator defined on the vortex boundary. The resulting generalized eigenvalue problem can then be solved numerically with spectrally-accurate discretizations. This approach is used to obtain new results about the stability of the family of vortex rings discovered by Norbury (1973). We find that while thin vortex rings remain neutrally stable to axisymmetric perturbations, they become linearly unstable when they are sufficiently "fat". Analysis of the structure of the eigenmodes demonstrates that they approach the corresponding eigenmodes of Rankine's vortex when the vortex ring is thin and the eigenmodes of Hill's vortex when the vortex ring is fat. These results are a stepping stone leading to a complete stability analysis of inviscid vortex rings with respect to general perturbations.

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MS84

Topological Data Analysis and Synchronisation of Covid-19 Epidemic Time Series

Data Science is a highly evolving discipline that presents many challenges. For example, in the case of an epidemic, how can we identify which socio-economic and social parameters, tourist mobility, prevention and control measures have the greatest impact on the dynamics of an epidemic? In recent years Topological Data Analysis has proved to be a powerful tool, a lens to highlight some dominant features of collective phenomena and explore large and complex data sets. In this talk we will see a brief introduction and how this new highly multidisciplinary tool - bringing together areas such as Space-Time Analysis, Algebraic Topology, Complex Networks, Linear algebra and Computation- is quite useful to characterise the COVID- 19 dynamics.

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MS84

Reconstruction of Interactions Among Coupled Oscillators: Application to Power Grids and Higher-Order Structures

In this talk I will discuss two recent results we have obtained on the reconstruction of interactions starting from measurements on the dynamical evolution of coupled nonlinear oscillators. The first one refers to power grids, modeled using a set of swing equations. These networks are subject to cascading failures whose characterization is fundamental for early detection and prompt control actions. With our method we are able to understand which lines are involved in the cascading process, even in situation when data are affected by noise. In the second part of the talk I will then discuss our findings on the reconstruction of interactions when oscillators are coupled not only through pairwise interactions, but also via higher-order mechanisms that involve three or more units. Also in this case we start from direct measuments on the temporal evolution of the node dynamics and set an optimization problem whose solution provides the estimates for the pairwise and higher-order connectivity underlying the observed dynamical behavior.

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MS86

Links Between Climate Tipping Elements: A Story of Ice, Overturning and Trade Winds

Nearly all climate models show a decrease in the strength of the Atlantic Meridional Overturning Circulation (AMOC) in the coming decades. A weakening, or shutdown, of this circulation has major impacts around the world. Firstly, in the Northern Hemisphere where it will induce wide-spread cooling impacting both sea-ice and the Greenland Ice Sheet (GIS). The corresponding change in the global distribution of heat impacts the atmospheric circulation. Where the response of the trade winds in the Atlantic is still relatively similar between models, this is not the case in the Pacific resulting in large uncertainty in the El Nino Southern Oscillation (ENSO) response. The GIS, sea-ice, AMOC and ENSO are known to be tipping elements within the climate system. In this talk I will discuss the links between them, starting with identifying causal links in CMIP6 model output which is needed to better inform conceptual models. The next question is whether tipping in e.g. the AMOC can induce tipping in the other systems, or whether observed changes simply correspond to movement along the same branch of the attractor without tipping the system.

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MS86

Dynamics of An Idealized Ghil-Zaliapin-Thompson Enso Model

The Ghil-Zaliapin-Thompson (GZT) model is a conceptual model of El Nino-Southern Oscillation (ENSO), stated as a scalar constant delay, periodically forced DDE

$$h'(t) = -\tanh(\kappa h(t-\tau)) + c\cos(2\pi t)$$

where $h(t)$ represents the deviation of the thermocline depth from its mean value in the eastern tropical Pacific Ocean, and also acts as an approximation to the sea surface temperature there. The delay arises due to the finite velocity of oceanic waves. Seasonal variation is included through periodic forcing, which makes the DDEs nonautonomous. The GZT model has been extensively studied numerically in recent years to reveal very complicated dynamics. For large c all stable invariant objects are period-one orbits, but for small c quasi-periodic and chaotic solutions may arise. We introduce an idealized or limiting case GZT model

$$h'(t) = -sign(h(t-\tau)) + c\cos(2\pi t)$$

which corresponds to taking the limit as $\kappa \to \infty$ in the smooth GZT model. For the idealized model we can explicitly construct periodic solutions and determine their stability. Thus we analytically find and study the curve of torus bifurcations bounding the region in the (τ, c) parameter plane where period one orbits are stable. We can also compute longer period orbits, and the associated phase locked regions where they exist. We compare and contrast these dynamics with those of the GZT model to help explain the observed dynamics in both models.

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MS86

Finite-Time Analysis of Regime Shifts and Crises in Conceptual Climate Models

In many applications, particularly those of weather and climate, there is a greater interest in local behaviour as opposed to asymptotic. For instance, if a chaotic attractor has imbedded regimes, a transition between regimes could have drastic impacts on the tangible effects in the physical system. In order to understand such transitions, we consider various local dynamical measures such as finite-time Lyapunov exponents, alignment of covariant Lyapunov vectors, and dimension measures based on the former two. Such measures are perhaps not only useful in regime transitions, as a recent study shows they may also indicate crises in systems of multiple chaotic attractors. We explore the measures on a paradigm example of a chaotic system along with a model of the AMOC forced by a chaotic signal.

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MS86

Modeling the Mid-Pleistocene Transition via Ramping Frequency Locking in An Energy Balance Model

About 1.2-1.3 million years ago the dominant periodicity of glacial cycles changed from ∼41 to ∼100 thousand years in an event now called the Mid Pleistocene Transition (MPT). We revisit the long-standing question of which dynamical processes could have triggered the MPT. We investigate this phenomenon using an Energy Balance Model with dynamic variables for latitudinally-averaged snow/albedo line and maximum ice extent. The model admits glacial cycles with similar spectral characteristics as the proxy records. We demonstrate that a critical bifurcation parameter is linked to a stack of benthic δ^{18}O records and that a realistic MPT can be reproduced via a mechanism known as Ramping with Frequency Locking. The details of how this mechanism occurs are determined by a bifurcation analysis of the model using numerical continuation.

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MS87

Koopman Von Neuman Wavefunction As Purified Square Root of Density Matrix: Implications for Semiclassical Limit and Quantum Classical Hybrids

We examine the little-known wave operator representation of quantum dynamics, and explore its connection to standard methods of quantum dynamics. This method takes as its central object the square root of the density matrix, and consequently enjoys several unusual advantages over standard representations. By combining this with purification techniques from quantum information, we are able to obtain a number of results. Not only is this formalism able to provide a natural bridge between phase and Hilbert space representations of both quantum and classical dynamics, we also find the waveoperator representation leads to novel semiclassical approximations of both real and imaginary time dynamics, as well as a transparent correspondence to the classical limit. Different applications of this methodology are outlined.

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MS87

Learning Closures of Dynamical Systems with Quantum Mechanics

We discuss a scheme for data-driven parameterization of unresolved dimensions of dynamical systems based on the mathematical framework of quantum mechanics and Koopman operator theory. Given a system in which some components of the state are unknown, this method involves defining a surrogate system in a time-dependent quantum state which determines the fluxes from the unresolved degrees of freedom at each timestep. The quantum state is a density operator on a finite-dimensional Hilbert space of classical observables and evolves over time under an action induced by the Koopman operator. The quantum state also updates with new values of the resolved variables according to a quantum Bayes' law, implemented via an operator-valued feature map. Kernel methods are utilized to learn data-driven basis functions and represent quantum states, observables, and evolution operators as matrices. The resulting computational schemes are automatically positivity-preserving, aiding in the physical consistency of the parameterized system. We analyze the results of two different modalities of this methodology applied to the Lorenz 63 and Lorenz 96 multiscale systems, and show how this approach preserves important statistical and qualitative properties of the underlying chaotic systems.

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MS87

Efficient Numerical Analysis of Optical Quantum Systems Via Bilinear Dynamic Mode Decomposition

In recent years, Koopman theory has given rise to straightforward yet powerful algorithms that allow for the description of non-linear dynamical systems using effectively linear techniques. In this presentation, our aim is to make use of the Koopman framework to predict the dynamics of optical quantum systems, which play a significant role in the development of quantum technologies. The analysis of these systems is often time-intensive and requires expensive numerical resources, emphasizing the need for elegant and efficient model predictions. Our particular research interest lies in quantum optimal control, where optical laser pulses are tailored regarding their amplitudes and frequencies to regulate the system behavior. We leverage the control-oriented bilinear dynamic mode decomposition (biDMD), which is an algorithm that uses actuated time-series measurements to approximate its Koopman operator with a finite set of autonomous operators. We present two variations of biDMD which vary in terms of the number of autonomous operators and compare their performances using the optical Bloch equations (OBE) of a two-level system as an example. These equations depend on the temporal envelope and the detuning of the exciting optical pulse and we compare time efficiency and accuracy of the two approaches, and demonstrate a speedup in comparison to an ordinary direct numerical integration.

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MS87

A Perspective on Solving Non-Linear Dynamical Systems with Quantum Computers

A number of recent studies have proposed that linear representations are appropriate for solving nonlinear dynamical systems with quantum computers, which fundamentally act linearly on a wave function in a Hilbert space. Linear representations, such as the Koopman representation and Koopman von Neumann mechanics, have regained attention from the dynamical-systems research community. Here, we aim to present a unified theoretical framework, currently missing in the literature, with which one can compare and relate existing methods, their conceptual basis, and their representations. We also aim to show that, despite the fact that quantum simulation of nonlinear classical systems may be possible with such linear representations, a necessary projection into a feasible finite-dimensional space will in practice eventually induce numerical artifacts which can be hard to eliminate or even control. As a result a practical, reliable and accurate way to use quantum computation for solving general nonlinear dynamical systems is still an open problem.

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MS88

Localised States in the Zhang-Vinals Equations

A layer of fluid on a rigid plate that is vibrated vertically in a periodic motion can display a fascinating range of patterns on its surface, termed Faraday waves. The form and stability of these patterns have been investigated theoretically since the first experimental reports of Faraday in 1831. We consider a simplified model, the so called Zhang–Viñals equations, which describe the Faraday setup for a fluid of low viscosity in a large aspect-ratio domain. It has been shown that the Zhang–Viñals model displays some of the fundamental dynamics necessary to explore pattern formation, with good qualitative agreement with the patterns observed in various experiments. The Zhang–Viñals equations have been numerically simulated using an exponential time differencing scheme. Temporally oscillating localised states, termed oscillons, are presented for a region within the parameter space where both the flat surface state and hexagonal patterns are stable. The parameters of the Zhang–Viñals equations relate directly to parameter values used in experiments where oscillons have previously been observed. The investigation of localised patterns within the model demonstrates how the theory of localised states can be applied to physical systems.

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MS88

Localized States in An Active Phase-Field-Crystal Model for Motility-Induced Crystallization

The passive conserved Swift-Hohenberg equation (or Phase-Field-Crystal [PFC] model) corresponds to a gradient dynamics for a single order parameter field related to density. It provides a microscopic description of the thermodynamics transition between liquid and crystalline states. In addition to spatially extended periodic structures, the model describes a large variety of steady spatially localized structures. In appropriate bifurcation diagrams the corresponding solution branches exhibit characteristic slanted homoclinic snaking in the form of a tilted snakes-and-ladders structure. A recent extension allows on to investigate both, liquid-solid and vapor-solid transitions. We discuss the snaking behavior of this passive, i.e., variational model. Subsequently we brake the gradient dynamics structure and analyze the influence of the non-variational terms on the localized states, employing both numerical path continuation and time simulations.

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MS88

Localized Patterns on Graphs

Studies on the existence branches of stationary localized patterns in bistable systems have been motivated by observed patterns such as in ferrofluids, urban crime spots, and vegetation models. We are interested here in bistable dynamical systems that are posed on graphs, and in particular on the impact of the graph structure on the shape of solution branches. Our studies focus on investigating how the solution curve of stationary localized patterns is affected by changes in the graphs when the coupling strength is close to the anti-continuum limit. We provide numerical simulations and analytical proofs for the case of simple ring graphs with symmetric coupling and varying interaction lengths. We will also show examples that extend to random graphs and demonstrate behaviors in different scenarios.

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MS88

Localized Patterns in a Nonlocal Vegetation Model

We analyze localized patterns from the nonlocal vegetation model proposed by Lefever and Lejeune (1997). We perform extensive continuation studies to analyze localized spike and gap solution and their counterparts in two-dimension. We investigate the transitions of these localized patterns in the continuation diagrams. We give ecological interpretations of our findings and discuss efficient numerical continuation methods for the nonlocal model.

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MS89

Data-Driven Stochastic Reduced Order Models for Burgers Equations

Trajectory-wise data-driven reduced order models (ROMs) tend to be sensitive to training data, and thus lack robustness. We propose to construct a robust stochastic ROM closure (SROM) from data consisting of multiple trajectories from random initial conditions. The SROM is a low-dimensional time series model for the coefficients of the dominating modes estimated by the proper orthogonal decomposition. Thus, it achieves reduction in both space and time, leading to simulations orders of magnitude faster than the full order model. We prove that both the estimated POD modes and parameters in the S-ROM converge when the number of trajectories increases. Thus, the S-ROM becomes robust. We demonstrate the S-ROM on a 1D Burgers equation with a viscosity $\nu = 0.002$ and with random initial conditions. The numerical results verify the convergence. Furthermore, the S-ROM makes accurate trajectory-wise predictions from new initial conditions and with a prediction time far beyond the training range, significantly outperforms the standard data-driven Galerkin ROM without closure, and quantifies the spread of uncertainties due to the unresolved scales.

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MS89

Learning the Dynamics of Time Delay Systems

A novel way of using neural networks to learn the dynamics of time delay systems from sequential data is proposed. A neural network with trainable delays is used to approximate the right hand side of a delay differential equation. We relate the delay differential equation to an ordinary differential equation by discretizing the time history and train the corresponding neural ordinary differential equation (NODE) to learn the dynamics. An example on learning the dynamics of the Mackey-Glass equation using data from chaotic behavior is given. After learning both the nonlinearity and the time delay, we demonstrate that the bifurcation diagram of the neural network matches that of the original system.

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MS89

The Spatio-Temporal Coupling in Delay-Coordinate DMD: Analysis and Applications

Dynamic mode decomposition (DMD) is a leading tool for equation-free analysis of dynamical systems from observations. Over the years, many extensions of DMD have been proposed. Among them, motivated by Takens embedding theorem, a combination of delay-coordinate embedding and DMD was presented. This combination, termed delay-coordinate DMD, has been shown useful in a broad range of cases where standard DMD becomes ineffective. In this work, we study the delay-coordinate DMD from a spatio-temporal perspective. An important property of DMD is the separation of the spatial information from the temporal information by the DMD modes and eigenvalues, respectively. We show that when DMD is applied to delay-coordinate embeddings, temporal information is mixed with spatial information, imposing a particular spatio-temporal structure on the DMD modes. We formulate this structure and reveal its dependency on the properties of the underlying dynamical system as well as on the number and dimension of the observations. Then, we utilize this structure and propose a new algorithm for the selection of DMD components. Such an algorithm is essential when delay-coordinate DMD is applied because it inherently generates redundant components. We demonstrate that our algorithm facilitates accurate characterization and reconstruction of a variety of dynamical systems,

showing improved performance compared to a commonly-used baseline that relies on the amplitude of the DMD components.

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MS90

Beyond Phase in Spatial Models

In prior work we considered a pure phase model in an annular domain, A, with nonlocal coupling:

$$u_t = \omega + \int_A W(x-y)H(u(y,t)-u(x,t))\ dy$$

and looked for rotating waves. We showed that the waves cease to exist as the hole in the annulus shrinks. This is a general feature of phase models because large phase gradients arise near the hole. However, if we extend beyond phase models to incorporate amplitude (e.g., via isostable reductions), then it is possible to shrink the hole. In fact, as the coupling gets stronger, the hole can shrink to zero. We show this in the normal form for a Hopf bifurcation, and if time permits, in a Wilson-Cowan type model.

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MS90

Parameter-Dependent Deformations of Phase Resetting Curves

Phase resetting is a common experimental approach to investigate neuronal dynamics. Assuming repeated spiking or bursting, a phase reset is a brief perturbation that causes a shift in the phase of this periodic motion. The observed effects depend on both the strength of the perturbation and the phase at which it is applied. The graph of the map from relation the unperturbed old phase to the new phase after the perturbation is called the phase resetting curve. Mathematically, resetting is closely related to the concept of isochrons of an attracting periodic orbit, which are submanifolds in the basin of attraction comprising all points that converge to the periodic orbit with a specific phase. A phase reset maps each isochron in the family of isochrons to another isochron in this family. Recently, we developed a numerical method that computes phase resetting curves in this precise context of mapping one isochron to another. The method is based on the continuation of a multi-segment boundary value problem and can be applied to systems of arbitrary dimension. In this talk, we show how this new approach can be used to study parameter-dependent deformations of phase resetting curves; we give a detailed overview of its properties, and investigate how the resetting behaviour is affected by phase sensitivity in the system.

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MS90

Phase-Amplitude Reduction for Stochastic Oscillators

We will discuss recent progress in extending the notions of phase and amplitude (or isostable) coordinates from the deterministic to the stochastic oscillator setting.

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MS90

Motor Robustness: Variational Analysis and Phase Reduction

Motor systems show an overall robustness, but because they are highly nonlinear, understanding how they achieve robustness is difficult. In many rhythmic systems, robustness against perturbations involves response of both the shape and the timing of the trajectory. This makes the study of robustness even more challenging. To understand how a motor system produces robust behaviors in a variable environment, we consider a neuromechanical model of motor patterns in the feeding apparatus of the marine mollusk *Aplysia californica* that operates within hard limits. We apply recently developed tools from variational analysis and phase reduction to explain in detail the robustness mechanism of the neuromechanical model against sustained perturbations such as increased mechanical load during swallowing, varying sensory feedback gain, or muscle strengths. The approaches that we are applying to understanding a neuromechanical model in Aplysia, and the results that we have obtained, are likely to provide insights into the function of other motor systems that encounter hard boundaries, both due to mechanical and neuronal firing properties.

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MS91

Reset-Induced Canard Cycles in Adaptive Integrate-and-Fire Neuron Models

We study a class of planar integrate and fire (IF) models called adaptive integrate and fire (AIF) models, which possesses an adaptation variable on top of membrane potential, and whose subthreshold dynamics is piecewise-linear (PWL). These AIF models therefore have two reset conditions, which enable bursting dynamics to emerge for suitable parameter values. Such models can be thought of as hybrid dynamical systems. We consider a particular slow dynamics within AIF models and prove the existence of bursting cycles with N-resets, for any integer N. Furthermore, we study the transition between N- and (N+1)-reset cycles upon vanishingly small parameter variations and prove (for N=2) that such transitions are organised by canard cycles. Finally, using numerical continuation we compute branches of bursting cycles, including canard-explosive branches, in these AIF models, by suitably recasting the periodic problem as a two-point boundary-value problem.

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MS91

Minimal Model of Potassium-Induced Saddle-Node-Loop Bifurcation

Neuronal firing alters ionic concentrations. In particular, intense or pathological activity can cause extracellular potassium accumulation, which affects back neurons' excitability. In common neuron models such as WangBuzski or Traub-Miles, extracellular potassium build-up induces a saddle-node-loop bifurcation. Beyond this codimension-two bifurcation, limit cycles corresponding to tonic firing arise from a homoclinic instead of SNIC bifurcation. This switch is suspected to be ubiquitous in conductance-based models where spike onset is mediated by a SNIC. It modifies essential dynamical aspects: presence of bistability, f-I curve continuity, phase response curve (PRC) symmetry. We develop a minimal model which captures this activity-induced transition and propose a method for deriving parameter values to mimic the dynamics of a given conductance-based model as accurately as possible. Our model is a two-dimensional slow-fast system. The voltage dynamics (fast component) is based on the QIF neuron, which we equip with a sodium-potassium pump. Action potentials progressively increment extracellular potassium (slow component), which drives the system to change regime through the pump electrogenic effect and an increase of the reset voltage. This model can reproduce interesting bursting behavior. Its simplicity also makes it a good candidate to investigate the role of potassium, via PRC reshaping, on neural synchronization in a network, for example in the context of epilepsy.

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MS91

Folded Saddles and Folded Homoclinic Bifurcations

Bursting oscillations are common in systems with multiple timescales, and are characterised by intervals of rapid spiking of the amplitude of one or more variables interspersed with quiescent periods during which the amplitude changes slowly. Recently, it was shown numerically that in a variety of multiple timescale systems, the onset of bursting and subsequent spike adding is associated with so-called folded homoclinic bifurcations, which can occur in systems with at least two slow variables when there is a homoclinic bifurcation in a particular singular limit of the system. It appears that no systematic study of this phenomenon has previously been done and the dynamics generically associated with a folded homoclinic bifurcation is not known. This talk will describe progress towards understanding the nature and origin of complex oscillations that arise from folded homoclinic bifurcations.

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MS91

Impacts of Timescale Separation on Control and Patterning of Neural Rhythms

Neural rhythms include dynamically-interesting activity

patterns at multiple levels, such as bursting in individual neurons, organized bursts of activity in a single population, and multi-phase rhythms involving several populations. In all of these cases, the combination of multiple processes acting on distinct timescales shapes the details of the emergent patterns, in ways that go beyond the standard classification of bursts in terms of pairs of (burst onset and burst offset) fast subsystem bifurcations. Moreover, slow-fast structure can strongly impact a neural system's response to control signals, ability to sustain a pattern over a broad parameter range, and capacity for bistability. I will discuss several recent findings about these effects, including some novel mathematical approaches taken to analyze the underlying dynamic mechanisms.

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MS92

Measurement of Human Entropy Production: Implications for Health and Illness

Complex living systems such as the human body are characterized by their self-organized and dissipative behavior where irreversible processes continuously produce entropy internally (as oxygen is metabolized to carbon dioxide) and exported to the environment. We hypothesize that thermodynamic entropy regulation acts as a driver for the maintenance of physiological stability. In this presentation, we will introduce our experimental approach for the continuous measurement of entropy flows in the human body using direct and indirect calorimetry. Participants of different age groups (young/middle-age/old), fitness level (trained/untrained) and with or without Type 2 diabetes performed exercise at varying intensity under heat stress in a calorimetry chamber. For fixed internal entropy production rates, we observed a progressive inability to externally dissipate entropy in older, untrained, or ill subjects, thus leading to greater entropy accumulation during exercise/heat stress, which we hypothesize is a measure of vulnerability. A phenomenological model of entropy regulation in humans, derived from these experimental insights, will also be discussed along with simulation results. This research aims for a novel understanding of human health and illness based on the study of non-equilibrium thermodynamics.

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MS92

Quantifying Physiological Trajectories of Preterm Infant Maturation

Preterm infants (born before 37 weeks gestation) are highly susceptible to sepsis, a life-threatening infection that can cause multi-organ dysfunction. By treating these infants with antibiotic therapy quickly, mortality and adverse long-term outcomes can be avoided, yet current gold standard for diagnosis sepsis is through blood cultures which can take up to 24 hours after clinical suspicion. Given our ability today to record and capture continuous physiological cardiorespiratory signals from these infants, a few studies have began looking at identifying biophysical markers that can be used to anticipate sepsis. Yet, many of these studies have looked at static biomarkers that are not adaptive to each infant. In this talk, I will be examining the dynamical trajectories that we have found in healthy versus septic infants, exploring the use of changepoint analysis and topological data analysis approaches to identify diverging pathways that could be used to provide earlier identification of sepsis in real-time.

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MS92

Mathematical Characterization of Preterm Infants Movement over Time

One in nine live births is preterm (<37 weeks gestational age). As the infant reaches full-term, the neuromotor circuits mature and the movement patterns of the infant change. Being able to quantify the normal development of movement for preterm infants could aid clinicians in making earlier diagnoses for movement disorders. In this study, we used a validated wavelet-based movement detection algorithm that identifies the movement bouts from the photoplethysmography (PPG) signal in preterm infants. We quantified movement patterns continuously in preterm infants who have spent more than eight weeks in the Neonatal ICU (NICU). The movement bouts were separated into 5 second intervals over 24 hours. The distribution of the lengths of bouts follows a power law relation. The exponent of the power law displays a linear relationship with gestational age, beginning around 30 weeks gestational age. This mathematical characterization of the change in movement patterns over time can assist in describing the normal development of a preterm infant.

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MS92

Advances in Improving Critical Healthcare Using Physiological Time Series Data

Physiological timeseries encode key information about a patient's health. In a growing trend, hospitals are utilizing data science teams to create and deploy clinical decision support tools to improve patient outcomes. This trend is due in part to the recent availability of systems to securely aggregate large amounts of physiologic patient data with no additional effort on researchers or clinicians. Many projects utilizing this data are focused on machine learning tools, which bring promise for developing predictive algorithms, but also suffer from biases, data drift, lack of generalizability, and other issues. Hence alongside these tools, mathematical tools which use first principles are crucial for improving healthcare using physiologic timeseries data. In this talk, I will review recent works which apply tools from mathematics and dynamical systems to physiologic timeseries data with the goal of saving lives in critical care environments.

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MS93

Deciphering Glioma Microenvironment Entry Mechanisms of Myeloid-Derived Suppressor Cells under Combination Immunotherapy Treatment

The highly immunosuppressive tumor microenvironment of glioblastoma multiforme (GBM) can hinder the ability of immune cells to effectively destroy cancer cells. Since the current treatment of GBM has so far been minimally effective, there is a need for new novel treatments such as immunotherapies. Monotherapy with the immune checkpoint inhibitor anti-PD-1 has failed to show efficacy in phase III clinical trials, however, murine experiments that administer combination treatment with anti-PD-1 and a CCR2 antagonist, which inhibits the recruitment of myeloid-derived suppressor cells (MDSCs) to the glioma, unmasked the immune checkpoint inhibitors ability to reduce tumor growth. Using a multidimensional ODE model, we analyze the immune dynamics of the glioma microenvironment. We then optimize administration of the combination immunotherapy with the overall objective being minimization of the tumor burden and MDSC entry as well as maximization of survival time.

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MS93

SMoRe ParS: A Novel Methodology for Bridging the Gap Between Experimental Data and ABMs of Cancer Growth and Treatment

Validated mathematical models of tumor growth mediated by complex microenvironmental interactions are increasingly recognized as invaluable for elucidating mechanisms that underlie experimental and clinical observations. Agent-based models (ABMs) provide a logical structure for capturing the multiple time and spatial scales associated with cancer growth and progression because they allow for the characterization of tumor heterogeneity at an individual cell level that better reflects the complexity seen in vivo. The inherent stochasticity and heavy computational requirements of ABMs are significant obstacles for data-driven parameterization and for conducting parameter space exploration and sensitivity analyses. Further, experimental data used for parameterization, is typically limited, coarse-grained and may lack spatial resolution, resulting in issues of parameter identifiability. There is hence a need for developing new theoretical and computational frameworks that can bridge the current divide between ABM parameters and real-world data. In this talk I will present a novel approach that uses explicitly formulated surrogate models (SMs) to bridge ABM simulations and experimental data. Our approach quantifies the relationship between parameter values across the ABM and SM and between SM parameters and experimental data. Thus, SM parameters act as interlocutors between ABM inputs and data that can be used for calibration and uncertainty quantification of ABM parameters.

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MS93

From Mechanistic Models of Prostate Cancer to Potential Clinical Biomarkers

The primary obstacle to effective long-term management for prostate cancer patients is the eventual development of treatment resistance. Due to the chaotic evolutionary trajectory of the cancer composition over the course of treatment, a drug is often applied continuously past the point of effectiveness. If a clinician is aware of the timing of resistance to a particular drug, then they may have a crucial opportunity to adjust the treatment to retain the drugs usefulness in a potential treatment combination or strategy. In this study, we investigate new methods of predicting treatment failure due to treatment resistance using a novel mechanistic model built on an evolutionary interpretation of Droop cell quota theory. We analyze our proposed methods using patient PSA and androgen data from a clinical trial of intermittent treatment with androgen deprivation therapy. Our results produce two indicators of treatment failure. The first indicator, proposed from the evolutionary nature of the cancer population, is calculated using our mathematical model with a predictive accuracy of 87.3%. The second indicator, conjectured from the implication of the first indicator, is calculated directly from serum androgen and PSA data with a predictive accuracy of 88.7% . Our results demonstrate the potential and feasibility of using an evolutionary tumor dynamics model in combination with the appropriate data to aid in the adaptive management of prostate cancer.

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MS94

Assessing the Impact of Covid-19 Mitigation Policies on Mental Health via Network Analysis

To manage the spread of the COVID-19 virus several federal and state-level health-related mandates were put in place in the United States, including lockdowns. These policies could have adverse effects on the mental health state of the populace. In this study, we assess the impact of COVID-19 policy actions on mental health in the United States using mental health-related indicators such as feeling anxious, feeling depressed, and worried about finances. We analyzed survey data from the Delphi Group at Carnegie Mellon University using clustering algorithms and dynamic connectome obtained by carrying out sliding window analysis. We found that between March 3rd, 2021, and January 10th, 2022, states in the south geographic region showed similar trends for reported values of feeling anxious and worried about finances. There were no identifiable communities clustering for feeling depressed. We observed a high degree of correlation among southern and republican states for feeling anxious and feeling depressed which seemingly overlapped with an increase in COVID-19-related cases, deaths, hospitalizations, and rapid spread of the COVID-19 Delta variant.

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MS94

Waning Immunity and a Pandemic of the Vaccinated

Since the start of the COVID-19 pandemic, much credence has been placed in the hope that widespread vaccination will lead to herd immunity, thus bringing the pandemic to its end. However, immunity attained through (currently available) vaccines is imperfect, and has been shown to wane over time. While vaccines have effectively reduced the risk of severe disease for millions, and have no doubt saved countless lives, mathematical models of viral spread among populations of mixed vaccination status show that the perception of a “pandemic of the unvaccinated” is overstated, and the impact of transmission events involving vaccinated individuals should be considered just as seriously. We present model simulations which demonstrate that, under certain conditions, the phase during which a majority of transmission events involve only unvaccinated individuals is short-lived, and ultimately dominated by events involving vaccinated individuals. This work is presented through the lens of the COVID-19 pandemic, however, in the broader epidemiological context, the ability to produce a highly effective vaccine which induces durable immunity could be a significant factor in determining the likelihood an emerging infection will become endemic. We consider the effect of imperfect vaccine-derived immunity on the dynamics of viral spread, finding that it can lead to vaccinated individuals predominating in both the infectious population as well as contribution to transmission events.

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MS94

Infection Induced Impacts on Population Dynamics in a Discrete-Time Epidemic Model

One-dimensional discrete-time population models, such as Logistic or Ricker growth, can exhibit periodic and chaotic dynamics. Expanding the system by one dimension to incorporate epidemiological interactions causes an interesting complexity of new behaviors. Previous work showed that infection that interrupts fecundity can lead to counter-intuitive increases in total population size, a phenomenon known as the hydra effect. Here, we examine a two-dimensional susceptible-infectious (SI) model with Ricker population growth and show that infection produces a distinctly different bifurcation structure than that of the underlying disease-free system. We use numerical bifurcation analysis to determine the influence of infection on the location and types of bifurcations. In addition, we examine the appearance and extent of the hydra effect upon the introduction of infection, particularly when the disease-free system has cyclic or chaotic dynamics. Our work shows that even in a simple two-dimensional SI model, the introduction of infection can produce dynamics that can shift the location of period-doubling bifurcations, the onset of chaos, and the appearance of the hydra effect.

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MS94

Gap Junctions and Synchronization Clusters in the Thalamic Reticular Nucleus

The Thalamic Reticular Nuclei (TRN) mediate processes like attentional modulation, sensory gating and sleep spindles. The GABAergic inter neurons in the TRN are known to exhibit widespread synchronized activity patterns. One known contribution to shaping synchronization and clustering patterns in the TRN is coming from the presence of gap junctions. These are organized in specific connectivity architectures, that have been identified empirically through dye and electrical coupling studies. We will present a computational model that implements both chemical synapses and gap junctions in realistic connectivity schemes, and we use it to investigate their differential role in TRN networks. In particular, we explore the potential effects of the size, strength and distribution of gap junctional clusters on the synchronization patterns, and how these effects are modulated by other factors, such as the level of background inhibition.

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MS95

Sampling-Dependent Transition Paths of Iceland-Scotland Overflow Water

We apply Transition Path Theory (TPT) from Markov chains to investigate the equatorward export of Iceland-Scotland Overflow Water (ISOW), a component of the "ocean's conveyor belt' controlling global climate. A recent analysis of observed trajectories of submerged floats demanded revision of the traditional abyssal circulation theory, which postulates that ISOW should steadily flow along a deep boundary current (DBC) around the subpolar North Atlantic prior to exiting it. The TPT analyses carried out here suggest that insufficient sampling may be biasing the this demand. The analyses, appropriately adapted to represent a continuous input of ISOW, are carried out on three time-homogeneous Markov chains modeling the ISOW flow. One uses a high number of simulated trajectories homogeneously covering the flow domain. The other two use much fewer trajectories which heterogeneously cover the domain. The trajectories in the latter two chains are observed trajectories or simulated trajectories subsampled at the observed frequency. While the densely sampled chain supports a well-defined DBC, the more heterogeneously sampled chains do not, irrespective of whether observed or simulated trajectories are used. Studying the sampling sensitivity of the Markov chains, we give recommendations for enlarging the float dataset to improve the significance of conclusions about time-asymptotic aspects of the ISOW circulation. Joint work with M.J. Olascoaga, L. Helfman and P. Miron.

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MS95

Transition Paths and Times of Sargassum in the Tropical North Atlantic

We consider E and Vanden-Eijnden's Transition Path Theory on discrete Markov chains with source A and target B. For both the finite and infinite time formulations of TPT, we compare a number of measures of the transition time between A and B. Among these is the "remaining time' which is the expected time remaining in a reactive trajectory starting from any state. This statistic can be computed in a straightforward manner and provides localized information about reactive trajectories. Applications will be given to undrogued drifter trajectory data from the NOAA Global Drifter Program, which has been used to model the transport of *Sargassum* in the tropical Atlantic. To apply discrete TPT, it is required that the trajectory data be binned according to—for example—Ulam's method in order to obtain a transition probability matrix. We will compare some binning algorithms with particular attention paid to methods which are not sensitive to the number of bins requested and which preserve graph connectedness. Joint work with F.J. Beron-Vera and M.J. Olascoaga.

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MS96

Drift-Rossby Waves Past the Breaking Point in Zonally-Dominated Turbulence

The spontaneous emergence of structure is a ubiquitous process observed in fluid and plasma turbulence. These structures typically manifest as flows which remain coherent over a range of spatial and temporal scales, resisting statistically homogeneous description. This work conducts a computational and theoretical study of coherence in turbulent flows in the stochastically forced barotropic β-plane quasigeostrophic (QG) equations. These equations serve as a prototypical two-dimensional model for turbulent flows in Jovian atmospheres, and can also be extended to study flows in magnetically confined fusion plasmas. First, analysis of direct numerical simulations demonstrate that a significant fraction of the flow energy is organized into coherent large-scale Rossby wave eigenmodes, comparable to the total energy in the zonal flows. A characterization is given for Rossby wave eigenmodes as nearly-integrable perturbations to zonal flow Lagrangian trajectories. Poincaré section analysis reveals that Lagrangian flows induced by the zonal flows plus large-scale waves exhibit localized chaotic regions bounded by invariant tori, manifesting as Rossby wave breaking in the absence of critical layers. It is argued that the surviving invariant tori organize the large-scale flows into a single temporally and zonally varying laminar flow, suggesting a form of self-organization and wave stability that can account for the resilience of the observed large-amplitude Rossby waves.

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MS96

Automated Discovery of Fundamental Variables Hidden in Experimental Data

All physical laws are described as mathematical relationships between state variables. These variables give a complete and non-redundant description of the relevant system. However, despite the prevalence of computing power and artificial intelligence, the process of identifying the hidden state variables themselves has resisted automation. Most data-driven methods for modelling physical phenomena still rely on the assumption that the relevant state variables are already known. A longstanding question is whether it is possible to identify state variables from only high-dimensional observational data. In this talk, I will present our recent work on determining how many state variables an observed system is likely to have, and what these variables might be. We demonstrate the effectiveness of this approach using video recordings of a variety of physical dynamical systems, ranging from elastic double pendulums to fire flames. Without any prior knowledge of the underlying physics, our algorithm discovers the intrinsic dimension of the observed dynamics and identifies candidate sets of state variables. In the end, I will also discuss how such efforts can be useful for robotics and computer vision applications.

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MS96

Statistical Reduced-Order Models and Closure Strategies for Turbulent Systems

The capability of using imperfect statistical reduced-order models to capture crucial statistics in turbulent systems is investigated. Much simpler and more tractable block-diagonal models are proposed to approximate the complex and high-dimensional turbulent dynamical equations through parametric closure models. New machine learning strategies are proposed to learn the expensive unresolved processes directly from data. A systematic framework of correcting model errors with empirical information theory is introduced, and optimal model parameters under this unbiased information measure can be achieved in a training phase before the prediction. It is demonstrated that crucial principal statistical quantities in the most important large scales can be captured efficiently with accuracy using the reduced-order model in various dynamical regimes of the flow field with distinct statistical structures.

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MS96

Finite Expression Method for Discovering Physical Laws from Data

Machine learning models are currently the tools of choice for uncovering physical laws from data in the era of data science. Although they have shown promising performance in prediction, their descriptions are often too verbose. This talk introduces a new methodology that seeks interpretable learning outcomes in the space of functions with finitely many analytic expressions and, hence, this methodology is named the finite expression method (FEX). It is proved in approximation theory that FEX can avoid the curse of dimensionality in discovering high-dimensional complex systems. As a proof of concept, a deep reinforcement learning method is proposed to implement FEX for learning various PDE systems.

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MS97

Teaching An Old Dog New Tricks: Rogue Waves, Floquet Solitons and Flat Bands in Different Variants of the Discrete NLS Equation

In this talk we will revisit nonlinear dynamical lattices, most notably of the discrete nonlinear Schrodinger (DNLS) type. We will explore some of their main features, including discrete solitons, discrete vortices and related structures in 1d, 2d and 3d, not only in square, but also in other lattice patterns (hexagonal, honeycomb, etc.). Then, motivated by recent experimental developments, we will consider some interesting variants on the theme, such as, e.g., what happens in Kagome' lattices. This will motivated a discussion of the notion of so-called flat bands and compactly supported nonlinear states therein. We will discuss simple methods of producing lattices with flat bands, and some experimental implementations thereof in electrical circuits. Finally, motivated by optical experiments, we will also extend considerations to topological 2d lattices with time-dependent interactions. In addition to considering the so-called Floquet solitons therein, including breathing generalizations of the DNLS states, we will see a case example where such a novel setting led to a new class of solutions in the original DNLS model.

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MS97

Multistability in Coupled Oscillator Systems with Higher-Order Interactions and Community Structure

We study synchronization dynamics in populations of coupled phase oscillators with higher-order interactions and community structure. We find that the combination of these two properties gives rise to a number of states unsupported by either higher-order interactions or community structure alone, including synchronized states with communities organized into clusters in-phase, anti-phase, and a novel skew-phase, as well as an incoherent-synchronized state. Moreover, the system displays a strong multistability, with many of these states stable at the same time. We demonstrate our findings by deriving the low dimensional dynamics of the system and examining the systems bifurcations using a stability analysis and perturbation theory. Finally, we discuss how phase lags in this system can lead to chaotic solutions.

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MS97

Transition Fronts and Their Universality Classes

Steadily moving transition fronts, bringing local transformation, symmetry breaking or collapse, are among the most important dynamic coherent structures. Nonlinear waves of this type play a major role in many modern applications involving the transmission of mechanical information in systems ranging from crystal lattices and metamaterials to civil engineering structures. While many different classes of such dynamic fronts are known, the relation between them remains obscure. In this talk I will consider a prototypical mechanical system, the FPU chain with bilinear interactions, and show that there are exactly three distinct classes of transition fronts, which differ fundamentally in how (and whether) they produce and transport oscillations. The availability of all three types of fronts as explicit solutions of the discrete problem enables identification of the exact mathematical origin of the particular features of each class. I will also present recent results on one type of transition waves, supersonic kinks, in problems with trilinear and fully nonlinear interactions. The talk is based on joint work with N. Gorbushin and L. Truskinovsky (ESPCI).

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MS98

Dynamics and Symmetries of Phase Oscillator Networks on Graph Limits

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MS98

Chaotic Heteroclinic Networks As Models of Switching Behavior in Biological Systems

Global activity in biological networks often transitions between many semi-stable states that correspond to dominant biological states, behaviors, or decisions. Transitions between these semi-stable states often appear to be random, and are modeled with stochastic models such as Markov chains. We propose that chaotic heteroclinic networks can be used to model stochastic switching phenomena. The models we build are low-dimensional, deterministic dynamical systems. Transitions between states are seemingly stochastic and dwell times vary due to chaos in the system. Choices of eigenvalues at saddle fixed points and functions used to connect their stable and unstable manifolds give quantitative control of the transition dynamics. As a proof of concept, we build models that fit the dynamics and switching statistics of *C. elegans* neural activity and show that Markov Model dynamics, often used to model state switching in neural dynamics, can be reproduced with this framework. Stochastic switching in our model is generated by deterministic dynamics; using this model we show that neural activity may randomly roam between various states without the necessity for noise.

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MS98

Uniformly Expanding Coupled Maps: Self-Consistent Transfer Operators and Propagation of Chaos

Recently, much progress has been made in the mathematical study of self-consistent transfer operators which describe the thermodynamic limit of globally coupled maps. Conditions for the existence of equilibrium measures (fixed points for the self-consistent transfer operator) have been given and their stability under perturbations and linear response have been investigated. One of the main questions remaining open is to which extent the thermodynamic limit describes the evolution of the finite dimensional system. In this talk, I am going to describe some novel developments answering this question for a system of N uniformly expanding coupled maps when N is nite but large. I will introduce self-consistent transfer operators that approximate the evolution of measures under the dynamics, and quantify this approximation explicitly with respect to N. Using this result, I will show that uniformly expanding coupled maps satisfy propagation of chaos when N tends to infinity, and I will characterize the absolutely continuous invariant measures for the finite dimensional system.

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MS98

Structural and Statistical Stability of Globally Coupled Dynamics

The response of high-dimensional chaotic systems to dynamical change is commonly expected to be smooth, but some very basic dissipative chaotic systems are known to be structurally and statistically unstable. Furthermore, the mechanisms behind this disjunction are not well-understood. To examine this, we consider a mathematically tractable example of a complex chaotic system, that of globally coupled systems. Considering a very general coupling of such systems to a slower variable, we show that globally coupled systems in the thermodynamic limit can approximate arbitrary low-dimensional dynamics, which may be structurally unstable and even exhibit wild dynamics. On the other hand, going from the thermodynamic limit to finite dimensions produces an emergent dynamical noise which regularises the statistical response of even quite unstable dynamical systems. This suggests that finite size of clusters of interacting systems is an important ingredient in the statistical stability of high-dimensional systems.

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MS99

Rate-Induced Tipping from Chaotic Attractors

There has been good progress on understanding instabilities in time-varying (non-autonomous) dynamical systems where the time-frozen systems have only equilibrium attractors. In particular, when the time variation is sufficiently rapid rate-induced tipping effects can appear. Such instabilities are particularly important in applications where a subsystem is being model but parameters in the system are varying. In this talk I will review progress on rate-induced tipping from more general attractors that are not necessarily equilibrium, and that may be chaotic. I will then discuss recent results with various collaborators on rate-induced tipping in cases where the time-frozen system has chaotic attractors, linking to results on various types of attractors for non-autonomous and random dynamical systems.

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MS99

Rate-Induced Tipping in Predator-Prey Systems

Nowadays, populations are faced with unprecedented rates of global climate change, habitat fragmentation and destruction causing an accelerating conversion of their living conditions. Critical transitions in ecosystems lead to sudden shifts in the dominance of species or even to species extinction and decline of biodiversity. We discuss a tipping mechanism which does not require alternative states but instead, the system performs a large excursion away from its usual behaviour when external conditions change too fast. During this excursion, it can embrace dangerously, unexpected states. We demonstrate that predator-prey systems can either exhibit a population collapse or an unexpected large peak in population density if the rate of environmental change crosses a certain critical rate. In reference to this critical rate of change which has to be surpassed, this transition is called rate-induced tipping (R-tipping). Whether a system will track its usual state or will tip with the consequence of either a possible extinction of a species or a large population peak like, e.g., an algal bloom depends crucially on the time scale relations between the ecological time scale and the time scale of environmental change. However, populations have the ability to respond to environmental change due to rapid evolution. We show how such kind of adaptation can prevent rate-induced tipping in predator-prey systems.

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MS99

Interactions of Noise and Transient Dynamics that Facilitate Tipping

Analyses of noise-induced tipping have been dominated by Freidlin-Wentzell (F-W) theory. This theory has its roots in the study of systems with underlying deterministic dynamics with a gradient vector field. F-W generalized the key results to non-gradient systems by introducing the concept of a quasipotential. A related but alternative view is in terms of the projection of an unstable manifold in the Hamiltonian system derived from the Euler-Lagrange equations for minimizing the action functional. A shortcoming of the F-W theory is that it requires vanishingly small noise and for many applications of interest, particularly in social, biological or environmental contexts, intermediate levels of noise are more appropriate. At such intermediate noise levels, the transient behavior of the underlying deterministic system becomes relevant, and I will explore how the above-mentioned dynamical systems viewpoint of sheds light on the effect of this interaction on tipping. The talk will center around two examples: (1) Escape through an unstable periodic orbit due to noise, and (2) The interplay of rate and noise induced tipping.

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MS99

When to Expect Rate-Induced Tipping in Natural and Human Systems

Over the last two decades, tipping points have become a hot topic due to the devastating consequences that they may have on natural and human systems. Tipping points are typically associated with a system bifurcation when external forcing crosses a critical level, causing an abrupt transition to an alternative, and often less desirable, state. However, the rate of change in forcing is arguably of even greater relevance in the human-dominated anthropocene, but is rarely examined as a potential sole mechanism for tipping points. Thus, I will introduce the related phenomenon of rate-induced tipping: an instability that occurs when external forcing varies across some critical rate, usually without crossing any bifurcations. First, I will explain when to expect rate-induced tipping. Then, using illustrating examples of differing complexity I will highlight universal and generic properties of rate-induced tipping in a range of natural and human systems.

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MS100

Rate-Induced Tipping in Heterogeneous Reaction-Diffusion Systems and Geographically Shifting Ecosystems

We propose a framework to study tipping points in reaction-diffusion equations (RDEs) with one spatial dimension, where the reaction term decays in space (asymptotically homogeneous), and varies linearly with time (nonautonomous) due to an external input. A compactification of the moving-frame coordinate together with Lins method to construct heteroclinic orbits along intersections of invariant manifolds allow us to: (i) obtain multiple coexisting pulse and front solutions for the RDE by computing heteroclinic orbits connecting equilibria at the infinities in the compactified moving-frame ordinary differential equation, (ii) detect tipping points as dangerous bifurcations of such heteroclinic orbits, and (iii) obtain tipping diagrams by numerical continuation of such bifurcations. We apply our framework to an illustrative model of a habitat patch that features an Allee effect in population growth and is geographically shrinking or shifting due to human activity or global warming. Thus, we identify two classes of tipping points to extinction: bifurcation-induced tipping (B-tipping) when the shrinking habitat crosses some critical length, and rate-induced tipping (R-tipping) when the shifting habitat exceeds some critical speed. We explore two-parameter R-tipping diagrams to understand how the critical speed depends on the size of the habitat patch and the dispersal rate of the population and uncover parameter regions where the shifting population survives.

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MS100

R-Tipping in a Microcosm Spatial Ecological System and Simple Models

This study combines simple models and experimental data from microcosms of flour beetles, Triblium castaneneum, designed to mimic the effects of the movement of suitable habitat along one spatial dimension with discrete habitat patches, as is resulting from climate change. In the experiments, if the rate of movement is to high relative to the other parts of the system, extinction results. The experimental setup allowed the determination of spatial population densities at all times. Distinctive spatial patterns arose before extinction. As a way to understand this system, simple discrete and continuous space, nonautonomous models were developed and demonstrated similar spatial patterns of population sizes with a lagging, in space, component. Even though the experiments were also discrete time, the models also considered continuous time. Given the match between experiment and model, these same signs should indicate impending extinction in other systems.

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MS100

Critical Transitions in D-Concave Non-Autonomous ODEs Appearing in Population Dynamics

A function with finite asymptotic limits gives rise to a transition equation between a "past system" and a "future system". We analyze this situation in the cases of nonautonomous coercive scalar ODEs with concave derivative with respect to the state variable, assuming the existence of three hyperbolic solutions for the limit systems, in which case the upper and lower ones are attractive. The different global dynamical possibilities are described in terms of the internal dynamics of the pullback attractor: cases of tracking of the two hyperbolic attractive solutions or lack of it (tipping) arise. This analysis allows us to present cases of rate-induced critical transitions, as well as cases of phase-induced and size-induced tipping. Our conclusions are applied in models of mathematical biology and population dynamics. We describe rate-induced tracking phenomena causing extinction of a native species or invasion of a non-native one. We also analyze population models affected by a Holling type III functional response to predation where tipping due to the changes in the size of the transition occurs. In all the cases, we see how the appearance of a critical transition can be understood as a consequence of the strength of the Allee effect.

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MS100

Rate-Induced Tipping in Earth's Carbon Cycle

Mysterious, abrupt, transient changes in the ocean's store of carbon occur intermittently throughout Earth's history. Each of these events coincides with climate change; moreover, mass extinctions are always accompanied by such events. What causes them? I suggest that many of these events are characteristic nonlinear responses of Earth's carbon cycle to influxes of carbon dioxide that exceed a critical rate. Analysis of the geologic record supports this view and a model of an excitable carbon cycle suggests how it works. The critical rate depends on the timescale T of carbon injection. In typical past events, T exceeds the carbon cycle's characteristic recovery time $\tau \sim 10^4$ years, and observational data provide an upper bound r^* for a unique critical rate. However, when $T \ll \tau$, the critical rate exceeds r^* by a factor of τ/T. Rates of carbon injection in the modern carbon cycle are roughly two orders of magnitude greater than r^*, while the modern injection timescale, about 10^2 years, is two orders of magnitude smaller than τ. The $1/T$ scaling of the critical rate therefore suggests that the modern carbon cycle is approaching a tipping point similar to that associated with major events of the geologic past.

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MS101

Chimeras and Singular Perturbation Theory

In this talk we provide some recent connections between the stability of complex patterns in adaptive networks and singular perturbation theory. Although the theory allows us to describe several synchronization patterns, we concentrate on chimera states in multilayer networks of phase-oscillators for which the coupling strenght(s) slowly change in time. This allows us to relate particular types of chimeras with particular types of attractors in the slow-fast mean field limit. We also discuss a few insights related to non-hyperbolic points (in the mean field) and their interpretation at the network level, and finish with a brief digression on open problems.

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MS101

Spectral Clustering of Directed and Time-Evolving Graphs Using Koopman Operator Theory

While spectral clustering algorithms for undirected graphs are well established and have been successfully applied to unsupervised machine learning problems ranging from image segmentation and genome sequencing to signal processing and social network analysis, clustering directed graphs remains notoriously difficult. We will first exploit relationships between the graph Laplacian and transfer operators and in particular between clusters in undirected graphs and metastable sets in stochastic dynamical systems and then use a generalization of the notion of metastability to derive clustering algorithms for directed and time-evolving graphs. The resulting clusters can be interpreted as coherent sets, which play an important role in the analysis of transport and mixing processes in fluid flows. We will illustrate the results with the aid of guiding examples and simple benchmark problems.

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MS101

Emergent Hypernetworks in Weakly Coupled Oscillators

Networks of weakly coupled oscillators had a profound impact on our understanding of complex systems. Studies on model reconstruction from data have shown prevalent contributions from hypernetworks with triplet and higher interactions among oscillators, despite the fact that such models were originally defined as oscillator networks with pairwise interactions. Here, we show that hypernetworks can spontaneously emerge even in the presence of pairwise albeit nonlinear coupling given certain triplet frequency resonance conditions. The results are demonstrated in experiments with electrochemical oscillators and in simulations with integrate-and-fire neurons. By developing a comprehensive theory, we uncover the mechanism for emergent hypernetworks by identifying appearing and forbidden frequency resonant conditions. Furthermore, it is shown that microscopic linear (difference) coupling among units results in coupled mean fields, which have sufficient nonlinearity to facilitate hypernetworks. Our findings shed light on the apparent abundance of hypernetworks and provide a constructive way to predict and engineer their emergence. This is based on joint work with Jorge Luis Ocampo-Espindola, Deniz Eroglu, Istvn Z. Kiss and Tiago Pereira.

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MS101

Decentralized Clustering of Stochastic and Dynamically Evolving Graphs

Decentralized clustering is an important problem that arises in a range of applications including satellite networks, social graphs, scalable computation, and uncertainty analysis to name a few. Recently, a decentralized approach to cluster large graphs was built that was based on propagating waves in the graph (using nearest neighbor updates) followed by a dynamic mode decomposition (DMD) step at every node. The computed DMD eigenvalues and modes are able to estimate the eigenvalues and the local components of the eigenvectors of the Laplacian matrix. In this work, we will extend this approach to compute the clusters in dynamically evolving graphs. In the dynamic graph setting, we will construct a decentralized incremental approach that estimates the change of the eigenvalues and eigenvectors due to the graph perturbation. In the stochastic setting, we will extend methods for the stochastic Koopman operator to estimate the graph partitions.

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MS102

Data-Driven Reduced Order Models for Optimal Control of High-Dimensional Systems

Modeling and control of high-dimensional, nonlinear robotic systems remains a challenging task. While various model- and learning-based approaches have been proposed to address these challenges, they broadly lack generalizability to different control tasks, rarely preserve the structure of the dynamics, and are unable to tractably bridge the gap between having accurate, but low-dimensional models. In this work, we propose a new, data-driven approach for extracting low-dimensional models from data using Spectral Submanifold Reduction (SSMR). In contrast to other data-driven methods which fit dynamical models to training trajectories, we identify the dynamics on generic, low-dimensional attractors embedded in the full phase space of the robotic system. This allows us to obtain computationally-tractable models for control which preserve the system's dominant dynamics and better track trajectories radically different from the training data. We demonstrate the superior performance and generalizability of SSMR in dynamic trajectory tracking tasks vis--vis the state of the art, including Koopman operator-based approaches.

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MS102

Spectral-Submanifold Reduction for Non-Smooth Dynamical Systems

Spectral submanifolds (SSMs) have recently been exploited as tools for exact model reduction for mechanical systems defined either by equations or by data sets. Specifically, for damped mechanical systems, SSMs have been found to capture amplitude-dependent physical properties, such as backbone curves or modal interactions, with high accuracy. Under external forcing, time-dependent SSMs have been shown to facilitate the fast computation of the frequency response and bifurcations. Moreover, SSM-based models allow both for the identification of geometric and material nonlinearities purely from data, and for the accurate prediction of system evolution for initial conditions. Open-source codes are now available for the automated extraction of SSMs from very high-dimensional finite elements models. However, all the available SSM developments are established for smooth dynamical systems. Here we discuss the relevance of SSMs for non-smooth or piecewise smooth dynamical systems, with a special regard to mechanical systems. In particular, we show that these manifolds still play a role in model order reduction for non-smooth systems. Additionally, we show in this talk how SSM-reduced models trained on decaying oscillations also predict forced response accurately. We will validate our theory on simple lumped oscillators and on finite element models with a large number of degrees of freedom.

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MS102

Data-Driven Inspection of Nonlinear Vibrations of Dehydrating Gelatin Plates

In engineering and biomedical applications, hydrogels are subjected to large amplitude dynamic loading. Besides, their water content depends on the operating conditions such as humidity and osmolarity. Recent studies have focused on linear vibrations of hydrogels whereas this study inspects their nonlinear vibrations. First, frequency sweep and resonance decay tests are conducted to monitor linear and nonlinear transverse vibrations of freshly cured gelatin plates under clamped boundary conditions. Then, spectral submanifolds (SSMs) are extracted from the resonance decay tests, and a single mode model of the plate is obtained. Finally, this data-driven model is validated against the frequency sweep responses measured. This protocol is repeated after dehydrating the gelatin plates for different durations. Water losses range between 20 to 40%. The linear modal frequencies are found to increase significantly with water loss. Dehydration-induced increase in Youngs modulus and built-up of in-plane stresses explain the increase in the modal frequencies. Furthermore, the SSM-based reduced order models uncover the dehydration-induced changes in nonlinear stiffness and damping properties of the gels. A slowly varying parametric representation of those models is obtained to account for the dehydration in the gels. This study pioneers characterization of nonlinear dynamics of hydrogels in real-time, while revealing the challenges in synthesis, handling, testing, and modeling of them.

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MS102

Model Reduction to Spectral Submanifolds: Classic Results and Their Latest Extensions

Machine learning has beena major development in applied science and engineering, with impressive success storiesin static learning environments like image,pattern, and speech recognition.Yetthemodeling of dynamical phenomenasuch as nonlinear vibrations of solids and transitions in fluidsremains a challenge forclassic machine learning. Indeed, neural net models for nonlinear dynamics tend to becomplex,uninterpretableand unreliable outside of their training range. In this talk, we survey a recent dynamical systems alternative to neural networks in the data-driven reduced-order modeling of nonlinear phenomena. Specifically, we show that the concept of spectral submanifolds (SSMs) provides very low-dimensional attractors in a large family of physical problems ranging from predicting wing oscillations to controlling soft robots. A data-driven identification of the reduced dynamics on these SSMs gives a rigorous way to construct accurate and predictive reduced-order models in solid and fluid mechanics without the use of governing equations. We briefly illustrate this on problems that include reduced-order modeling of fluid sloshing in a tank, acceleration of finite-element simulations from data, identification of material nonlinearities of hydrogels and model-predictive control of soft robots. The other speakers in this two-part MS will expand on these and other problems in more detail.

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MS103

Localized Dissipative Vortices in a Frustrated Chiral Liquid Crystal

Solitons have played a fundamental role in understanding nonlinear phenomena and emergent particle-type behaviors in out-of-equilibrium physics. 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 dynamics behavior. Chiral nematic liquid crystals (CNLC) under geometrical frustration are a natural habitat to observe localized vortices, also called chiral bubbles. This frustration is imposed by introducing the CNLC into a cell with homeotropic anchoring. Even though chiral bubbles have been observed and studied since a long time ago, their creation and destruction mechanisms and their respective bifurcation diagrams are unknown. We propose a minimal two-dimensional Ginzburg-Landau model based on experimental observations of a temperature-triggered first-order winding/unwinding transition of a cholesteric liquid crystal cell and symmetry arguments to further understand localized dissipative vortices. This model reveals the main ingredients for the emergence of chiral bubbles and their instabilities: energy difference, topology, and chirality. Experimental observations have quite fair agreement with the theoretical results.

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MS103

Going Around in Circles: A Radial Spatial Dynamic Theory for Fully Localised 2D Patterns

The emergence of small-amplitude localised patterns is rigorously well understood in one spatial dimension, thanks in part to the theory of spatial dynamics developed by Kirchgssner in the 1980s. A key concept in this approach is treating an unbounded spatial direction as a 'time-like' variable and using tools from dynamical systems to prove the existence of localised (in 'time') solutions. However, a key question emerges when considering higher spatial dimensions; how can one use such an approach to study patterns that are localised in multiple directions? Such patterns are often found in experiments and yet there is very little analytic theory regarding them, beyond a handful of examples. In this talk, we will focus on 2D patterns that are localised in the radial direction and explore the theory of radial spatial dynamics, introduced by Scheel in 2003. We will review prior studies of axisymmetric patterns, before presenting recent results for approximating fully localised patterns with dihedral symmetries. Throughout we will highlight connections to the 1D problem, how new classes of solutions can emerge in this framework, as well as some of the difficulties encountered when considering nonlinear PDEs in polar coordinates.

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MS103

Resonant Travelling Wave Solutions to Weakly Nonlinear Models

In this work, we consider some common weakly nonlinear models for water waves that exhibit resonant travelling wave solutions. We show asymptotically how resonances arise for different models and compare and contrast the results for several commonly used linear operators, including the regimes where these asymptotic results fail

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MS104

Data-Driven Modelling of How Disinformation and Conspiracy Theories Propagate in Social Networks

Anonymous image boards such as 4chan are hosts to a wide variety of conspiracy theories and political memes that spread on other social networks. We use large scale datasets obtained from Twitter, 4chan, Gab, and Telegram, all public social networks where political misinformation is known to be frequent, to examine the propagation of political content among these different sources. We develop a data-driven, stochastic dynamical model of the influence of anonymous image-boards on wider social media discussion. Using this model, we quantify the worst-case effects of a hypothetical deliberate and targeted misinformation campaign and discuss potential mitigating strategies.

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MS104

Constructing Integro-PDEs for the Emergent Dynamics of Agent-Based Simulations on Mimesis in Financial Markets: A Machine Learning Approach

We address a machine learning framework for the construction of effective coarse-grained Integro-Partial Differential Equations (Integro-PDE) describing the emergent behavior of Agent-Based Models (ABMs) and in particular of an agent-based Monte-Carlo simulator approximating the dynamics of a simplistic financial market with mimesis [Siettos, et al. (2012), EPL, 99(4), 48007]. Based on high-fidelity spatio-temporal data, using Gaussian Process regression, we discover, a set of effective macroscopic variables that parametrize a low-dimensional manifold on which the emergent distributed dynamics evolve, and based on them find the closures required to construct low-dimensional macroscopic PDEs using two machine learning approaches, namely Deep Feedforward Neural Networks (DFNNs) and single-layer Random Projection Neural Networks(RPNNs). Finally, based on the learned Integro-PDE, we construct the coarse-grained bifurcation diagram of the average market efficiency with respect to the average number of social links of the agents, exploiting the numerical bifurcation analysis toolkit [Fabiani, G. et al. (2021). J. Sc. Comp., 89(2), 1-35]. We show that the learned PDEs approximate accurately the coarse-grained bifurcation diagram constructed using the Equation-free approach. We also show that the proposed RPNNs outperform the classical DFFNs in terms of numerical accuracy and computational cost, thus being about 30 times faster in the training phase.

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MS105

Analyzing the Sensitivity of Nonlinear Oscillators to Parametric Perturbations Using Isostable and Isochron Coordinates

A key consideration for nonlinear oscillators is how they respond to parametric perturbations; such changes in parameters can often lead to effects on both the amplitude and phase of these oscillators. When the underlying process is sensitive to these changes, there may be large effects on the system leading to unwanted conditions. Additionally, models for nonlinear oscillators are often high-dimensional and intractable, making analysis in terms of the original coordinates nonintuitive. Utilizing an isostable and isochron coordinate frame, the transient dynamics of nonlinear oscillators to parametric perturbations can be analyzed in a convenient way by making use of the response curves from augmented phase reduction. Although isochron and isostable coordinates are convenient to use in analysis, typically one is interested in understanding what happens in terms of the original variables, and thus, a coordinate recovery framework is devised to take the results from the isostable and isochron frame back to the original coordinates. This approach shows great promise for understanding the transient behavior of nonlinear oscillators due to parametric perturbations.

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MS105

High-Order Accuracy Computation of Coupling Functions for Strongly Coupled Oscillators

We develop a general framework for identifying phase reduced equations for finite populations of coupled oscillators that is valid far beyond the weak coupling approximation. This strategy represents a general extension of the theory from [Wilson and Ermentrout, Phys. Rev. Lett 123, 164101 (2019)] and yields coupling functions that are valid to arbitrary orders of accuracy in the coupling strength. These coupling functions can be used understand the limiting behavior of potentially high-dimensional, nonlinear coupled oscillators in terms of their phase differences. The proposed formulation accurately replicates nonlinear bifurcations that emerge as the coupling strength increases and is valid in regimes well beyond those that can be considered using classic weak coupling assumptions. We demonstrate the performance of our approach through two examples. First, we use the analytically tractable complex Ginzburg-Landau (CGL) model and demonstrate that our theory accurately predicts bifurcations far beyond the range of existing coupling theory. Second, we use a realistic conductance-based model of a thalamic neuron and show that our theory correctly predicts asymptotic phase differences for non-weak coupling strengths. In both examples, our theory accurately captures model behaviors that existing theories cannot.

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MS105

An Adaptive Phase-Amplitude Coordinate Framework Valid for Strongly Perturbed Oscillatory Systems

I will discuss recent work that considers the dynamics of a limit cycle oscillator in reference to a continuous family of limit cycles that result from static shifts in parameters. In conjunction with phase-based model order reduction techniques, this approach yields analytically tractable reduced order models that are valid in the strongly perturbed regime, in other words, they do not require restrictive order epsilon limitations on the magnitude of the perturbations. In practice, this approach allows for the consideration of large magnitude inputs in situations where other standard phase-amplitude reduction methods fail. Applications will be discussed that involve control of neural rhythms, multi-generator power systems, and fluid flow past obstacles.

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MS106

Front Propagation inTwo-Component Reaction-Diffusion Systems with a Cut-Off

The Fisher-Kolmogorov-Petrowskii-Piscounov (FKPP) equation with a cut-off was popularised by Brunet and Derrida in the 1990s as a model for many-particle systems in which concentrations below a given threshold are not attainable. While travelling wave solutions in cut-off scalar reaction-diffusion equations have since been studied extensively, the impacts of a cut-off on systems of such equations are less well understood. As a first step towards a broader understanding, we consider various coupled two-component reaction-diffusion equations witha cut-off in the reaction kinetics, such as an FKPP-type population model of invasion with dispersive variability due to Cook, a FitzHugh-Nagumo-style model with piecewise linear Tonnelier-Gerstner kinetics and, finally, a more general FKKP-type system with a cut-off in both components that is motivated by models for the spatial spread of hitchhiking traits. Throughout, our focus is on the existence, structure, and stability of travelling fronts, as well as on their dependence on model parameters; in particular, we determine the correction to the front propagation speed that is due to the cut-off. Our analysis is for the most part based on a combination of geometric singular perturbation theory and the desingularisation technique known as "blow-up".

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MS106

Emergence of Tipping in a Slow-Fast Cellular Automaton Modelling Tropical Forest-Fire Feedback

Tropical forests have been hypothesised to exist as alternative stable states to tropical savannas, implying that they may collapse abruptly under gradually increasing pressure due to climate change or deforestation. A key assumption in its proposed mechanism is that fires spread on grass and are effectively blocked by forest, which is as a consequence only damaged near its edges. We simulate a recently proposed probabilistic cellular automaton that obeys these rules. Taking into account that spreading processes occur near the forest perimeter, with fire spread occurring on the fast and forest spread on the slow time scale, we find an emergent relation between forest structure and macroscopic dynamics. This relation matches simulations with high accuracy and can hence be used to test where fire-vegetation feedbacks are strong enough to cause bistability and tipping.

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MS106

Morphogen-Directed Cell Fate Boundaries: Slow Passage Through Bifurcation and the Role of Folded Saddles

One of the fundamental mechanisms in embryogenesis is the process by which cells differentiate and create tissue structures important for multicellular organism functioning. Morphogenesis involves the diffusive process of chemical signalling involving morphogens that pre-pattern the tissue and which influence cell fate through a nonlinear process of transcriptional signalling. In this paper, we consider this multiscale process in an idealised model for a growing domain. We focus on intracellular processes that lead to robust differentiation into two cell lineages through interaction of a single morphogen species with a cell fate variable that undergoes a bifurcation from monostability to bistability. We investigate conditions that result in robust pattern formation into two well-separated domains, as well as conditions where this fails and produces a pinned boundary wave where only one part of the domain grows. We show that successful and unsuccessful patterning scenarios can be characterised in terms of presence or absence of a folded saddle singularity for a system with two slow variables and one fast variable; this models the interaction of slow morphogen diffusion, slow parameter drift through bifurcation and fast transcription dynamics. We show how this approach can successfully model acquisition of three cell fates to produce ‘French flag’ patterning, as well as for a more realistic model of cell fate dynamics in terms of two mutually inhibiting transcription factors.

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MS106

Diversity-Induced Decoherence in a Slow-Fast Dynamical System

The effects of noise and heterogeneity (or diversity) on neural dynamics have been extensively studied. Some studies emphasized the possibility of amplifying the response of a network to an external signal driven by noise or diversity. Other studies highlighted that noise or diversity could generate significant resonance effects, even without an external signal, causing coherent oscillations. An example of the latter kind is self-induced stochastic resonance (SISR). On the other hand, a few works have analyzed the combined effects of noise and diversity in neural dynamics. These studies mostly led to the conclusion that adding optimal diversity on top of noise results in a further enhancement of resonance effects caused by noise alone, i.e., the role of optimal diversity is always constructive. However, in this talk, we use the mean-field approach, slow-fast analysis, and numerical simulations to demonstrate that, in contrast to previous literature, showing that network diversity can always be optimized to enhance collective behaviors such as synchronization or coherence, the effect of diversity on SISR, instead, can only be antagonistic – a nontrivial effect which we call diversity-induced decoherence (DIDC). Our result indicates that diversity's enhancement or deterioration of noise-induced resonance phenomena strongly depends on the underlying mechanism.

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MS107

Predicting Complex Spatiotemporal Electrical Dynamics in Live Human Hearts: a Novel Reservoir Computing Approach

Predicting complex nonlinear time series is a challenging task made even more difficult with the inclusion of space, such as behavior of cardiac tissue during arrhythmias. Nevertheless, even relatively short-term predictions of complex cardiac electrical dynamics in space could be useful for improving existing treatments or developing new therapeutical approaches. In this talk, we demonstrate a novel method for predicting the spatiotemporal electrical dynamics of cardiac tissue using an echo-state network integrated with a convolutional autoencoder. We show that our approach can forecast complex spiral-wave-breakup several periods in advance for time series ranging from model-derived synthetic datasets to optical-mapping recordings of explanted human hearts.

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MS107

Estimation of Electrical Activation in the Heart from Local Deformations Using Neural Networks

Cardiac arrhythmias are a major health problem. As the local electrical activation triggers mechanical contraction of the muscle fibers, an aberrant electrical pattern causes suboptimal pumping of blood. A classical approach to diagnose and analyse cardiac arrhythmias occurs via the electrical signals. However, in recent years it was shown that excitation patterns such as traveling waves and rotors in the heart can also be observed via their effect on the mechanical deformation [Christoph, J. et al. Electromechanical vortex filaments during cardiac fibrillation. Nature 555, 667672 (2018)], [Grondin J. et al. 4D cardiac electromechanical activation imaging. Comput Biol Med. 2019 Oct]. Here, we present a novel approach to infer the electrical pattern from local deformation using an underlying physics-based model. The combination of deep learning with physical constraints enables to recover detailed activation maps from local displacements in the presence of noise. Results are shown for simulated data and an outlook on analysing clinical data is given.

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MS107

Reconstructing Spatiotemporal Chaos in Three-Dimensional Excitable Media

The cardiac muscle is an excitable medium that can exhibit complex dynamics, including spatiotemporal chaos associated with (fatal) cardiac arrhythmias. On a small scale, cardiac tissue consists of interacting cardiac muscle cells embedded in an extracellular matrix. These cells interact electrically and mechanically, and their (in-)coherent motion is triggered by the propagation of electrical excitation waves, including spiral or scroll waves during ventricular fibrillation. Electrical excitation can be measured optically using fluorescent dyes, but only at the surface of Langendorff-perfused isolated hearts. Therefore, a method to reconstruct the excitation inside the muscle based on surface data is needed. One possible approach to this reconstruction is the utilization of artificial neural networks (ANNs) that are trained on simulations of cardiac dynamics and later applied to real experimental data. To estimate the feasibility of this method, we trained and tested different ANNs on a simple model of isotropic, chaotic excitable media on a regular grid. Our investigations show that the reconstruction of these high-dimensional chaotic states is possible in principle, but as expected its quality depends on the network architecture used and in general decreases with increasing reconstruction depth. In our contribution we will present and discuss these results as well as extensions using different models and alternative machine learning methods.

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MS107

Predicting Cardiac Dynamics Using Deep Learning

In the heart, nonlinear waves of electrical excitation trigger mechanical contractions. The dynamics can become very complex, particularly during heart rhythm disorders, such as ventricular or atrial fibrillation. To date, it is a challenge to observe and visualize these dynamics, because they can only be measured partially or indirectly. In this talk, we introduce the current challenges in the field and discuss the potential to reconstruct cardiac wave dynamics using deep learning. We specifically discuss how convolutional neural networks can be used to denoise and interpolate measurement data, cross-predict electrical dynamics from tissue mechanics, infer fully three-dimensional dynamics from two-dimensional or otherwise partial observations, track discrete features such as phase singularities, and be trained on simulated and subsequently be applied to experimental data. This talk provides an overview and a basis for the following talks in this minisymposium.

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MS108

Network Immuno-Epidemiological Model of HIV and Opioid Epidemics

In this talk we introduce a novel multi-scale network model of two epidemics: HIV infection and opioid addiction. The HIV infection dynamics is modeled on a complex network. We determine the basic reproduction number of HIV infection and opioid addiction. We show that the model has a unique disease-free equilibrium which is locally asymptotically stable when both $\mathcal{R}_u$ and $\mathcal{R}_v$ are less than one. If $\mathcal{R}_u > 1$ or $\mathcal{R}_v > 1$, then the disease-free equilibrium is unstable and there exists a unique semi-trivial equilibrium corresponding to each disease. We performed numerical simulations to better understand the impact of three epidemiologically important parameters that are at the intersection of two epidemics: q_v the likelihood of an opioid user being infected with HIV, q_u the likelihood of an HIV-infected individual becoming addicted to opioids, and δ recovery from opioid addiction. Simulations suggest that as the recovery from opioid use increases, the prevalence of co-affected individuals, those who are addicted to opioids and are infected with HIV, increase significantly. We demonstrate that the dependence of the co-affected population on q_u and q_v are not monotone.

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MS108

Will Cross-Immunity Protect the Community from Covid-19 Variants?

The emergence of new SARS-COV-2 variants significantly threatens the efficacy of COVID-19 vaccines. Not only can variants be potentially more infectious than the wild-type strain, but they may also partially evade existing vaccines. A two-strain, two-group mechanistic mathematical model is designed to assess the impact of the vaccine-induced, cross-protective efficacy COVID-19 transmission in the United States. If the wild-type strain co-circulates with a variant strain that is twice as transmissible as the wild-type strain, then 82% of the US population must be fully-vaccinated to achieve vaccine-derived herd immunity. Global sensitivity analysis of the model shows which parameters are the most influential in driving the reproduction number of the variant strain in the US. New SARS-CoV-2 variants that are only moderately more transmissible than the wild-type strain will not cause an outbreak surge in the US if at least 66% of the US population is fully-vaccinated by vaccines offering a moderate level of cross-protection against the variant.

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MS108

Predicting Extinction of Multiple Ecosystem Competing Populations (such as Covid Strains) via a Team of Lyapunov Functions

This talk will introduce a new class of Lyapunov functions that will be useful when competing populations die out. Each such system may have many Lyapunov functions that work together to reveal the long-term fate of populations. These Lyapunov functions are used to reveal behaviors other than the existence of a stable equilibrium, which will not exist if populations are dying out. For certain population equations, we show some species die out exponentially fast. Hence, we refer to die-out Lyapunov functions. We also introduce trapping region Lyapunov functions which can reveal the existence of a global trapping region.

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MS109

How Differences in Inducible Defenses Alter Predator-Prey Dynamics

Prey species have a variety of defenses to avoid being eaten by predators. Inducible defenses change during an individual's lifetime and include changes in prey behavior (e.g., hiding more when predators are around) and morphology (e.g., growing larger spines when more predators are around). Across species, inducible defenses vary in terms of the speed of induction (e.g., a rapid behavioral change versus slow growth of a defensive structure) and the stimuli that cause induction (e.g., responses solely driven by cues from predators versus responses driven by cues from predators and prey). Inducible defenses can affect the abundances and dynamics of prey and predators, and those effects depend on the speed of induction and the cues driving the inducible response. In this talk, I present and analyze a coupled ODE model of a predator-prey system with an inducible prey defense. I explore how differences in induction rates and the cues driving the induced responses alter the stability and cyclic dynamics of the system. For example, my results show that inducible defenses driven by predator cues are stabilizing whereas inducible defenses driven by predator and prey cues can be destabilizing when cues from prey density strongly inhibit defense induction (e.g., prey do not induce when prey densities are high). My results generalize prior modeling studies of inducible defenses and help explain why inducible defenses often have stabilizing effects in empirical systems.

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MS109

Simple and Complex Dynamical Systems in Fisheries Management and Conservation

Simple and complex models from mathematical biology can aid environmental decisions. However, both simple and complex models can be costly. Simple models are often unable to predict unexpected negative effects of management. While large, complex models can predict perverse outcomes, their predictions are often inaccurate due to overfitting and their sensitivity to small perturbations in parameter values, model structure, and initial conditions. So how complex should our models be? In this talk, I will go back to the basics and discuss some of the simplest models used to manage fisheries including some of the costs and benefits of these various modeling approaches.

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MS109

Deriving Reproduction Number Expressions for Arbitrarily Large, Finite-Dimensional Systems of ODEs Using the Generalized Linear Chain Trick

Reproduction numbers play important roles in the analysis and application of dynamic models, including infectious disease models and ecological population models. One difficulty in deriving these quantities is that they are often computed on a model-by-model basis, since it is typically impractical to obtain general reproduction number expressions applicable to a family of related models, especially if these are of different dimensions as is the case with SIR-type infectious disease models derived using the linear chain trick (LCT). In this talk, I show how to find general reproduction number expressions for such models families using the next generation operator approach in conjunction with the generalized linear chain trick (GLCT). Importantly, the GLCT enables modelers to draw insights from these results by leveraging theory and intuition from continuous time Markov chains (CTMCs) and their absorption time distributions (i.e., phase-type probability distributions). Reproduction number derivations for two model families will be presented: a flexible family of generalized SEIRS models of arbitrary finite dimension, and a generalized family of finite dimensional predator-prey (Rosenzweig-MacArthur type) models. These results highlight the utility of the GLCT for the derivation and analysis of mean field ODE models, especially when used in conjunction with theory from CTMCs and their associated phase-type distributions.

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MS109

Mathematical Modeling of Retinal Degeneration: Insights into Pathological Mechanisms and Interventions

Cell degeneration, including that resulting in retinal diseases, is linked to metabolic issues. In the retina, photoreceptor degeneration can result from an imbalance in lactate production and consumption as well as disturbances to glucose and pyruvate levels. We analyze a novel mathematical model for the metabolic dynamics of a cone photoreceptor, which is the first model to account for energy generation from fatty acid oxidation of shed photoreceptor outer segments. Multiple parameter bifurcation analysis shows that joint variations in key parameter ranges affect the cones metabolic vitality and its capability to adapt under glucose-deficient conditions. Time-varying global sensitivity analysis is used to assess the sensitivity of model outputs of interest to changes and uncertainty in the parameters at specific times. The results reveal a critical temporal window where there is more flexibility for therapeutic interventions to rescue a cone cell from the detrimental consequences of glucose shortage.

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MS110

Quantifying Extreme Precipitation with Enhanced Sampling and Transition Path Theory

The weather is said to have “a mind of its own,’ as a chaotic system with limited predictability. Yet its fluctuations remain largely confined to a familiar probability distribution, to which the built and natural environment is well adapted. More impactful are the extreme, intermittent fluctuations of temperature, moisture, and wind, which can seriously threaten ill-equipped human and ecological communities. Extreme events have “dynamics of their own’ which are difficult to quantify because they play out in a far tail of the probability distribution, and so sample sizes are limited in both observations and simulations. Rare event sampling, e.g. ensemble-splitting, is a promising strategy to augment the available data. This presentation will demonstrate the results of ensemble-splitting to generate extreme, long-lasting precipitation in an idealized atmospheric model. By focusing our computational efforts on extreme events, we can visualize the associated synoptic patterns and compute return periods with greater statistical confidence. Moreover, this enables a more efficient exploration of parameters, such as convection schemes, latitude-dependence, and global warming. Technical challenges as well as opportunities will be discussed.

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MS110

Pathway-Specific Statistics Using Augmented Transition Path Theory

Transition path theory provides a statistical description of the dynamics of a reaction in terms of local spatial quantities. In its original formulation, it is limited to reactions that consist of trajectories flowing from a reactant set to a product set. We extend the basic concepts and principles of transition path theory to reactions in which trajectories exhibit a specified sequence of events. We apply this generalization to separate and characterize individual reaction pathways of two systems: a simple 3D potential with overlapping pathways and the folding pathways of the Trp-cage miniprotein. Joint work with J. Weare and A.R. Dinner.

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MS110

Exploring the Use of Transition Path Theory in Oil Spill Forecasting

Transition Path Theory (TPT) has proven a robust means for statistically characterizing the ensemble of trajectories connecting any two preset flow regions, A and B, directly, that is, starting in A they go to B without detouring back to A or B. Here, we explore its use for building a scheme that enables predicting the evolution of an oil spill in the ocean. This involves appropriately adapting TPT such that it includes a reservoir that pumps oil into a typically open domain. Additionally, we lift up the restriction of the oil not to return to the spill site en route to a region that there is interest to be protected. TPT is applied on oil trajectories available up to the present, e.g., as integrated using velocities produced by a data assimilative system, to make a prediction of transition oil paths beyond, without relying on forecasted oil trajectories. As a proof of concept we consider a hypothetical oil spill in the Trion oil field, under development within the Perdido Foldbelt in the northwestern Gulf of Mexico, and the *Deepwater Horizon* oil spill. This is done using trajectories integrated from climatological and hindcast surface velocity and winds as well as produced by satellite-tracked surface drifting buoys, in each case discretized into a Markov chain that provides a framework for the TPT-based prediction. Joint work with F.J. Beron-Vera.

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MS111

Combining Stochastic Parameterized Reduced Order Models with Machine Learning for Data Assimilation and Uncertainty Quantification with Partial Observations

A hybrid data assimilation algorithm is developed for complex dynamical systems with partial observations. After a spectral decomposition, a machine learning model builds a nonlinear map between the coefficients of observed and unobserved state variables for each spectral mode. A cheap low-order nonlinear stochastic parameterized extended Kalman filter (SPEKF) model is employed as the forecast model in the ensemble Kalman filter to deal with each mode associated with the observed variables. The resulting ensemble members are then fed into the machine learning model to create an ensemble of the corresponding unobserved variables. The training residual in the machine learning-induced nonlinear map is further incorporated to advance the quantification of the posterior uncertainty. The hybrid data assimilation algorithm is applied to a precipitation quasi-geostrophic (PQG) model, which includes the effects of water vapor, clouds, and rainfall beyond the classical two-layer QG model. The complicated nonlinearities in the PQG equations prevent traditional methods from building simple and accurate reduced-order forecast models. In contrast, the SPEKF model is skillful in recovering the intermittently observed states, and the machine learning model effectively estimates the chaotic unobserved signals. Utilizing the calibrated model under a moderate cloud fraction, the results remain accurate when applied to other scenarios with nearly clear skies or relatively heavy rainfall.

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MS111

Exploring Use of Artificial Intelligence Towards Practical Data Assimilation Problems

Data assimilation for numerical weather prediction using the operational system ingests a wide range of spatially and temporary irregular, heterogeneous observations to re-initialize the state through optimization. Both model state obtained by forecast from the last initialization and observations are subject to noise and errors. Conventionally, operational data assimilation involves empirical data selection and quality control of observations in the ingestion process. In this presentation, two examples of machine learning/artificial intelligence approach for are shown: i) intelligent empirical data selection and quality control; and ii) emulation of observation operators and their Jacobians.

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MS111

Lagrangian Tracer Recovery through Stochastic Models and Filtering

The assimilation and prediction of a flow field given a stream of measurements provided by passively advected Lagrangian drifters is discussed. We quantify recovery of the Eulerian energy spectra from observations of Lagrangian drifters by special Lagrangian data assimilation algorithms, based on conditionally Gaussian Kalman filters. Prediction of the Eulerian energy slope is demonstrated through combined assimilation and parameter estimation, and recovery skill of the spectrum in various regimes is demonstrated

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MS111

Application of Machine Learning in Subgrid-Flux Parametrization of Turbulent Models

We present a machine learning approach for developing stochastic parametrizations of subgrid fluxes in finite-volume discretizations of PDEs expressed in flux form. In particular, we utilize Generative Adversarial Networks (GANs) to parametrize subgrid fluxes in equations for coarse variables defined via spatial filtering. We discuss how to construct and train the network and demonstrate that our approach reproduces statistical properties of coarse variables in fully resolved simulations. Moreover, we also demonstrate that GANs are robust and can be utilized without re-training in new regimes (e.g. changes in forcing). We use Burgers and Shallow-Water equations to illustrate our approach.

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MS112

Andronov-Hopf Bifurcations in Rank-Three Bimolecular Mass-Action Systems

We systematically address the question of which small bimolecular reaction networks endowed with mass-action kinetics are capable of Hopf bifurcation. It is easily shown that any such network must have at least 3 species and at least 4 reactions, and its rank is at least 3. Terming the class of n-species, m-reaction, rank-r networks as (n, m, r) networks, we are able to fully classify bimolecular (3,4,3) networks: with the extensive help of computer algebra, we divide these networks into those which forbid Hopf bifurcation and those which admit Hopf bifurcation. Beginning with 14670 bimolecular (3,4,3) networks which admit positive equilibria, we show that the great majority of these are incapable of Hopf bifurcation. At the end of this process, we are left 138 networks with the potential for Hopf bifurcation. These fall into 87 distinct classes, up to a natural equivalence. Out of the 87 classes we find that 86 admit nondegenerate Hopf bifurcation (supercritical, subcritical, or both). The remaining exceptional class robustly admits a vertical Hopf bifurcation. Finally, we can use the results on bimolecular (3,4,3) networks, along with previously developed theory on inheritance, to predict the occurrence of Hopf bifurcation in networks with more species and/or reactions. Thus, in fact, finding all small networks with the capacity for Hopf bifurcation greatly expands our knowledge of which reaction networks, not necessarily small, admit Hopf bifurcation.

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MS112

Toric Differential Inclusions, the Global Attractor Conjecture, and the Persistence Conjecture

Any dynamical system with polynomial right-hand side can essentially be regarded as a model of a reaction network. Key properties of reaction network models are closely related to fundamental results about global stability in classical thermodynamics. For example, the *Global Attractor Conjecture* can be regarded as a finite dimensional version of Boltzmanns H-theorem. We will discuss some of these connections, and we will focus especially on introducing *toric differential inclusions* as a tool for proving the Global Attractor Conjecture. We will also discuss some implications for the more general *Persistence Conjecture* (which says that solutions of any weakly reversible system cannot "go extinct"), as well as some applications for biochemical mechanisms that implement *noise filtering and cellular homeostasis*.

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MS112

The Structure of the Moduli Spaces of Toric Dynamical Systems

We consider complex-balanced mass-action systems or toric dynamical systems. They are remarkably stable polynomial dynamical systems from reaction networks seen as Euclidean embedded graphs. We study the moduli spaces of toric dynamical systems, called the toric locus: given a reaction network, we are interested in the topological structure of the set of parameters giving rise to toric dynamical systems. We show that the complex-balanced equilibria depend continuously on the parameter values. In particular, we emphasize its product structure: it is homeomorphic to the product of the set of complex-balanced flux vectors and the affine invariant polyhedron.

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MS112

Dynamic Absolute Concentration Robustness in Biochemical Reaction Networks

In a reaction network, a species has dynamic absolute concentration robustness (dynamic ACR) if its concentration converges to a fixed value (called ACR value) independent of the initial values of the overall system. Dynamic ACR provides a mechanism for output robustness in a biochemical system operating in a highly variable environment. Experimental work has identified networks with dynamic ACR in thousands of bacterial signaling circuits. A mathematical characterization of dynamic ACR is challenging because it requires establishing convergence properties for arbitrary initial values. We take a significant step in this direction by proposing a normal form for the differential equation of the dynamic ACR variable. The normal form gives a formula for certain "fuel" and "load" functions, which are roughly functions that help and hurt prospects of convergence. We give sufficient conditions on fuel and load which result in convergence to the ACR value. We explicitly study an archetypal ACR network, its relation to the normal form, and the consequences of coupling with a chemostat, an apparatus that allows for inflows and outflows of reagents.

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MS113

The Maslov Index and Noise-Induced Tipping

In this talk, we will describe recent analytical and computational tools to identify Most Probable Escape Paths (MPEPs) in stochastic dynamical systems (SDEs). The study of noise-induced tipping has been dominated by Freidlin-Wentzell (FW) theory. A drawback of the FW theory is that it necessitates vanishingly small noise. However, for several applications of interest, particularly in environmental, biological or social contexts, intermediate noise is of more relevance. In focusing on the intermediate noise regime, the transient behavior of the underlying deterministic system will play a key role. We will thus use a dynamical system approach to identify MPEPs in SDEs. The Maslov index will help us distinguish which critical points of the FW functional are minimizers and help explain the effect of the interaction of noise and transient dynamics. Our computations will then be compared with Monte Carlo simulations in order to verify theoretical predictions in the Inverted Van der Pol system.

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MS113

Most Probable Transition Paths in Piecewise-Smooth SDEs

We develop a path integral framework for determining most probable paths for a class of systems of stochastic differential equations with piecewise-smooth drift and additive noise. This approach extends the Freidlin-Wentzell theory of large deviations to cases where the system is piecewise-smooth and may be non-autonomous. In particular, we consider an $n-$dimensional system with a switching manifold in the drift that forms an $(n-1)-$dimensional hyperplane and investigate noise-induced transitions between metastable states on either side of the switching manifold. To do this, we mollify the drift and use $\Gamma-$convergence to derive an appropriate rate functional for the system in the piecewise-smooth limit. The resulting functional consists of the standard Freidlin-Wentzell rate functional, with an additional contribution due to times when the most probable path slides in a crossing region of the switching manifold. We explore implications of the derived functional through two case studies, which exhibit notable phenomena such as non-unique most probable paths and noise-induced sliding in a crossing region.

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MS113

The Unexpected Helpfulness of Adding Noise to Nonsmooth ODEs

In this talk I will survey some positive effects of adding noise (randomness) to Filippov systems. Filippov systems are ODEs with discontinuous right-hand sides for which solutions can evolve (slide) on a discontinuity surface. They are fraught with issues regarding non-uniqueness of solutions and non-continuity of solutions with respect to smoothing and it is interesting that the addition of noise can alleviate some of these issues. It can help justify the use of a simple Filippov model as opposed to one that describes transitions smoothly, it can resolve the non-uniqueness of forward evolution along the intersection of discontinuity surfaces, and, together with certain singularities (two-folds), it can be used as a mechanism for randomising the phase of a collection of oscillators.

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MS114

Resource-Mediated Competition Between Two Plant Species with Different Rates of Water Intake

We propose an extension of the well-known Klausmeier model of vegetation to two plant species that consume water at different rates. Rather than competing directly, the plants compete through their intake of water, which is a shared resource between them. In semi-arid regions, the Klausmeier model produces vegetation spot patterns. We are interested in how the competition for water affects the co-existence and stability of patches of different plant species. We consider two plant types: a thirsty species and a frugal species, that only differ by the amount of water they consume per unit growth, while being identical in other aspects. We find that there is a finite range of precipitation rate for which two species can co-exist. Outside of that range (when the rate is either sufficiently low or high), the frugal species outcompetes the thirsty species. As the precipitation rate is decreased, there is a sequence of stability thresholds such that thirsty plant patches are the first to die off, while the frugal spots remain resilient for longer. The pattern consisting of only frugal spots is the most resilient. The next-most-resilient pattern consists of all-thirsty patches, with the mixed pattern being less resilient than either of the homogeneous patterns. We also examine numerically what happens for very large precipitation rates. We find that for a sufficiently high rate, the frugal plant takes over the entire range, out-competing the thirsty plant.

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MS114

Vegetation Pattern Formation in Drylands: Impacts of Changing Storm Characteristics

A beautiful example of spontaneous pattern formation occurs in certain dryland environments around the globe. Stripes of vegetation alternate with stripes of bare soil, with striking regularity and on a scale readily monitored via satellites. Though the vegetation is a showstopping spectacle, water, which is the limiting resource for these ecosystems, is the unseen player behind the scenes. Water concentrates into the vegetated zones, essentially reinforcing vegetation patterning, via positive feedbacks, and its dynamics play out on the short timescales of the rare storms. In contrast, the vegetation may change very little over decades. I will describe a stochastic pulsed precipitation model framework that allows us to capture the impacts of variability in storm characteristics, such as storm intensity and duration, as well as seasonality. We identify an intrinsic length scale associated with these storm characteristics that sets the vegetation pattern scale in the model. This work is motivated by the question of how these vulnerable ecosystems might respond to climate change which may lead to increased variability in storm intensity.

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MS114

Multi-Level Ecosystem Response to Climate Change

Ecosystem response to drier climates is likely to employ stress-relaxation mechanisms operating at different levels of ecological organization. At the individual level, a plant can change its phenotype, e.g., from a shallow root plant to a deep root plant to reach a moister soil layer. At the population level, plants can self-organize in spatial patterns, a process that involves partial plant mortality and increased water availability to remaining plants. At the community level, shifts from fast-growing species to stress-tolerant species can occur. These mechanisms are naturally coupled, but their interplay has hardly been studied. In this talk, I will present model studies of the interplay between phenotypic changes and vegetation patterning and between vegetation patterning and community re-assembly. I will show that phenotypic transitions from shallow-roots to deep-roots plants can result in multiscale vegetation patterns and increased resilience to drier climates. I will further show that spatial patterning can result in a homeostatic plant community that keeps its composition and diversity unchanged, despite the development of a drier climate, because of spatial re-patterning. Understanding pathways of ecosystem response, where mechanisms operating at different organization levels act in concert, is essential for assessing the actual resilience of ecosystems at risk and devising management practices to evade tipping points.

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MS114

Effect of Surface Curvature on Pattern Formation

Motivated by studies and observations of how vegetation patterns are impacted by curved terrains, we study pattern formation in reaction-diffusion systems posed on curved manifolds. For dynamics of large amplitude localized spot patterns far from the spatially homogeneous state, we use a matched asymptotics approach to reduce the problem to the computation of local behaviors of certain Green's functions near the singularity. We briefly discuss a numerical-analytic method for computing the required quantities. In the weakly nonlinear regime, we discuss how a small amplitude stripe pattern on a flat manifold is perturbed when the manifold itself is slightly curved.

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MS115

Solving Systems of Partial Differential Equations Through Quantum Computing

Recently we have developed quantum algorithms for solving the Navier-Stokes equations governing the motion of classical fluids, as well as arbitrary systems of partial differential equations. In this talk we briefly describe the construction of these quantum algorithms and the regimes where they provide a quantum speed-up. We then discuss ongoing work extending these algorithms in multiple directions. First, we describe quantum circuits that implement the quantum oracles appearing in these algorithms so that they are now expressed entirely as quantum circuits. We then discuss how the original spatial discretization based on finite-difference methods can be replaced by: (i) finite-element; (ii) finite-volume; and (iii) spectral methods. Lastly, we discuss the extension of the quantum Navier-Stokes algorithm to problems in magnetohydrodynamics and plasma dynamics. We emphasize that these quantum algorithms open up a large new application area for quantum computing quantum simulation of classical nonlinear continuum systems and fields which have substantial economic and scientific impact.

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MS115

Demonstration of Algorithmic Quantum Speedup

Despite the development of increasingly capable quantum computers, an experimental demonstration of a provable algorithmic quantum speedup employing today's non-fault-tolerant devices has remained elusive. In this talk, I will report on the first demonstration of such a speedup, quantified in terms of the scaling of time-to-solution with problem size. The demonstration is based on the single-shot Bernstein-Vazirani algorithm which efficiently solves the problem of identifying a hidden bitstring that changes after every oracle query. We implemented this algorithm utilizing two different 27-qubit IBM Quantum superconducting processors. The speedup is observed when the computation is protected by dynamical decoupling an open-loop quantum control protocol designed to suppress noise due to the environment but not without decoupling. In contrast with recent quantum supremacy demonstrations, the quantum speedup reported here does not rely on complexity-theoretic conjectures.

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MS115

Transfer Operators on Quantum Platforms

Transfer operator theory has been successfully applied to problems from various research areas such as fluid dynamics, molecular dynamics, climate science, engineering, and biology. Applications include detecting metastable or coherent sets, coarse-graining, system identification, and control. In a recent article [Klus, Nske, Peitz 2022] it has been discussed how data-driven techniques from the transfer-operator approach to dynamical systems can be used to open a new avenue to solving the Schrdinger equation. In this contribution, we turn the question around and ask how quantum computing can be used to harvest the power of transfer operator techniques for analyzing complex systems.

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MS115

Koopman Operator Theory for Quantum Simulation of Classical Dynamics

We present a framework for simulating a measure-preserving, ergodic dynamical system by a finite-dimensional quantum system amenable to implementation on a quantum computer. The framework is based on a quantum feature map for representing classical states by density operators on a reproducing kernel Hilbert space, H, of functions on classical state space. Simultaneously, a mapping is employed from classical observables into self-adjoint operators on H such that quantum mechanical expectation values are consistent with pointwise function evaluation. Meanwhile, quantum states and observables on H evolve under the action of a unitary group of Koopman operators in a consistent manner with classical dynamical evolution. The state of the quantum system is projected onto a finite-rank density operator on a 2^n-dimensional tensor product Hilbert space associated with n qubits. The finite-dimensional quantum system is factorized into tensor product form, enabling implementation through an n-channel quantum circuit with $O(n)$ gates. Furthermore, the circuit features a quantum Fourier transform stage with $O(n^2)$ gates, which makes predictions of observables possible by measurement in the standard computational basis. We illustrate our approach with quantum circuit simulations for low-dimensional dynamical systems, as well as actual experiments on the IBM Quantum System One.

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MS116

Deciphering Experimental Nonlinear Sloshing Resonances of Water in An Oscillating Tank Using SSM

Fluids in partially filled tanks exhibit sloshing waves when subjected to oscillations close to their resonance frequency. For the design of e.g. rocket and tank ships it is crucial to predict resonances with models, because a coupling of the fluid motion to e.g. the bending modes of the rocket is infeasible for simulations. Models based on the equations of potential flow theory are typically used to predict slosh-

ing resonances in tanks, but these are not able to reliably predict nonlinear resonances.
In this talk we present accurate experimental measurements of sloshing water waves in a rectangular tank subjected to horizontal harmonic oscillation. We determine the nonlinear response curves of the sloshing amplitude and the phase lag for wide ranges of driving amplitudes and fill levels. Quasi-linear dynamics, period-three motions and competition between flow states were observed in the softening and hardening regimes. Our experimental data is ideally suited to test and develop model equations and especially data-driven reduced-order models of nonlinear resonances. Comparisons of the experiments to models typically used to predict sloshing resonances will be briefly shown. The focus of the modelling will be on data-driven spectral submanifold theory, which is presently the only model capable of predicting the measured nonlinear response curves (see *Cenedese et al.*, Nat. Comm. 2022).

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MS116

Data-Assisted Reduction of Finite-Element Models via Spectral Submanifolds

Despite the broad availability of dedicated software packages for finite element simulations, the computation and continuation of the steady-state in response of nonlinear mechanical systems to periodic forcing remains a serious computational challenge for full-scale nonlinear finite element models. The theory of Spectral Submanifolds (SSM) has laid the foundation for a rigorous model reduction of such nonlinear systems, leading to reliable steady-state response predictions within feasible computation times. Further developments have made the direct computation of such invariant manifolds and their reduced dynamics scalable to realistic, nonlinear finite-element models. More recently, dynamics-based machine learning has enabled a data-driven computation of SSMs from unforced trajectory simulations performed over commercial finite element software. In this talk, we demonstrate these recent advances towards the computation of SSMs with applications covering realistic finite-element models in a non-intrusive/data-driven setting.

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MS116

Modeling Transitions in Shear Flows Using Reduced-Order Models on Spectral Submanifolds

Several approaches have been proposed to derive reduced-order models for exact coherent states (ECSs), and transitions among them in canonical shear flows. Popular data-driven approaches include linear methods, such as Dynamic Mode Decomposition (DMD) and Koopman mode expansion. However, these approaches cannot produce reduced models that capture fundamentally nonlinear phenomena, such as coexisting ECSs and transitions among them. The theory of spectral submanifolds (SSMs) offers an alternative for reduced-order modeling of phenomena involving coexisting ECSs. These structures, SSMs, are very low dimensional attracting invariant manifolds that emanate from stationary states and have the potential to connect those states to other coexisting stationary states. Recent advances have enabled the identification of SSMs purely from numerical or experimental data. Here we apply these results to construct SSMs of simple ECSs in plane Couette flow. We show that physically relevant quantities, such as the rate of energy input and dissipation rate can be used to parametrize the most important SSMs connecting coexisting ECSs. By restricting the dynamics to these SSMs, we obtain accurate reduced-order models that capture all asymptotic states of the full Navier-Stokes equations. A similar approach is expected to apply to pipe flow to possibly capture the geometrical aspects of the subcritical transition to turbulence.

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MS116

Model Reduction for Constrained Mechanical Systems via Spectral Submanifolds

Dynamical systems are often subject to algebraic constraints in conjunction to their governing ordinary differential equations. In particular, multibody systems are commonly subject to configuration constraints that define kinematic compatibility between the motion of different bodies. A full-scale numerical simulation of such constrained problems is challenging, making reduced-order models (ROMs) of paramount importance. In this work, we show how to use spectral submanifolds (SSMs) to construct rigorous ROMs for mechanical systems with configuration constraints. These SSM-based ROMs enable the direct extraction of backbone curves and forced response curves, and facilitate efficient bifurcation analysis. We demonstrate the effectiveness of this SSM-based reduction procedure on several examples of varying complexity, including nonlinear finite-element models of multi-body systems. We also provide an open-source implementation of the proposed method that also contains all details of our numerical examples.

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MS117

Clustering Solutions Arising Via Hopf Bifurcation

We consider a network of Wilson-Cowan oscillators, with homeostatic adjustment of the inhibitory coupling strength and time delayed, excitatory coupling. We study the existence of Hopf bifurcations induced by the excitatory coupling and determine how these bifurcations lead to different patterns of phase-locked oscillations, i.e., clustering solutions. We show how interaction between different Hopf bifurcations can lead to complex solutions, such as intermittent synchronization.

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MS117

Emergence of Chimera States in a Neuronal Model of Delayed Oscillators

Neurons are traditionally grouped in two excitability classes, which correspond to two different responses to external inputs, called phase response curves (PRCs). In this work, we have considered a network of two neural populations with delayed couplings, bound in a negative feedback loop by a positive PRC (type I). Making use of both analytical and numerical techniques, we derived the boundaries of stable incoherence in the continuum limit, studying their dependance on the time delay and the strengths of both interpopulation and intrapopulation couplings. This led us to discover, in a system with stronger delayed external compared to internal couplings, the coexistence of areas of coherence and incoherence, called chimera states, that were robust to noise. On the other hand, in the absence of time delays and with negligible internal couplings, the system portrays a family of neutrally stable periodic orbits, known as breathing chimeras.

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MS117

Novel Modes of Synchronization in Star Networks of Coupled Chemical Oscillators

Photochemically coupled micro-oscillators are studied experimentally and computationally in star networks to investigate the modes and mechanisms of synchronization. The micro-oscillators are catalyst-loaded beads that are placed in catalyst-free BelousovZhabotinsky (BZ) solutions. The properties of the photochemical coupling between the oscillators are determined by the composition of the BZ reaction mixtures, and both excitatory coupling and inhibitory coupling are studied. Synchronization of peripheral oscillators coupled through a hub oscillator is exhibited at coupling strengths leading to novel modes of synchronization of the hub with the peripheral oscillators. A theoretical analysis provides insights into the mechanism of the synchronization. The heterogeneous peripheral oscillators have different phase velocities that give rise to a phase divergence; however, the perturbation from the hub acts to realign the phases by delaying the faster oscillators more than the slower oscillators.

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MS117

Clustering Solutions in Pulse Coupled Model of Firefly-Flashing

A wide variety of biological systems can be modeled as a coupled oscillator system. These sorts of mathematical systems can exhibit behaviors such as synchronization, traveling waves, clusters, or chimeras where multiple patterns can exist simultaneously. Previously, swarms of fireflies have been of interest as a biological system of oscillators that appear to synchronize their flashing. This synchrony inside the swarm builds up as the night goes on, where fireflies slow up or speed down their flashing to become in phase with its neighbors. Recent research involved real-world data on flashing behavior of firefly swarming and shown that this behavior is more complicated that previously modeled. In this talk, we model a system of pulse coupled oscillators to represent the flashing of fireflies and investigate the effects of different parameters on cluster size. We use values to mimic previous data and look at both global coupling and a more physiological nonlocal coupling and result in dynamics.

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MS118

Wasserstein Distances in the Analysis of Dynamical Networks

Introducing the Wasserstein distance for time series analysis is not new. More than a decade ago, Muskulus and Verduyn-Lunel demonstrated how to measure the similarity between time series whose empirical probability densities form invariant measures in the limit of infinite time spans (Physica D 240(1), 45-58, 2011). Yet, applications of this approach remain scars, arguably for two reasons. First, estimating Wasserstein distances between time series is computationally demanding and, second, the proposed statistical evaluation is limited which limit intelligibility of results limited. While the first challenge seems less prevalent given improved computational capacity and memory access, the second one will be central to this talk. In brief, a combination of permutation testing and bootstrapping will be presented as it can serve to make statistically robust classifications of dynamical states via the Wasserstein distance. This approach will be exemplified in a variety of settings, starting with an analysis of the Hnon system as resemblance of the original paper. The approach, however, is not limited to low-dimensional systems. This will be illustrated by studying different large-scale dynamical systems including different types of phase oscillator networks with probability densities on an N-torus.

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MS118

Classification of Bursting Patterns: Mind the Slow Variables

In this talk, I will first generalise a recent example that falls outside of the standard bursting classification systems and that requires the analysis of both fast and slow subsystems of an underlying slow-fast model. I will show experimental data that can motivate the development and study of such bursting models. This new class of bursters with at least two slow variables will be denoted *folded-node bursters*, to convey the idea that the bursts are initiated or annihilated via a *folded-node singularity*. Key to this mechanism are so-called canard orbits, organizing the underpinning excitability structure. I will describe the two main families of folded-node bursters, depending upon the phase (active/spiking or silent/non-spiking) of the bursting cycle during which folded-node dynamics occurs. I will classify both families and give examples of minimal systems displaying these novel bursting patterns. Finally, I will provide a biophysical example by reinterpreting a generic conductance-based episodic burster as a folded-node burster, showing that the associated framework can explain its subthreshold oscillations over a larger parameter region than the fast-subsystem approach.

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MS118

Multiscale Virtual Brain Modeling for Clinical Translation in Ebrains

The past two decades have seen enormous progress in the development of virtual brain technologies, primarily due to progress in brain imaging and high-performance computing. Virtual brains integrate an individuals brain imaging data into a computational representation of a brain model and make it a personalized in-silico brain simulation platform. Since its initial proposal in 2002, virtual brains have been systematically built for the mouse, macaque and human and their individual predictive value has been established, regularly outperforming generic brain models. Virtual brains are constructed from an individuals connectivity and are mathematically captured by functional differential-integral equations with time delays as a function of propagation distance. In case of injury or disease, such as stroke, neurodegeneration or epilepsy, the communication between brain areas is impaired and results in pathological brain activity. All data are integrated through application of techniques in Bayesian inference and Monte Carlo simulation, in which generic high-resolution brain templates are morphed to accommodate the patients brain imaging data, leading to a maximum predictive power for a given individual. We illustrate the virtual brain workflow along the example of drug resistant epilepsy, the so-called Virtual Epileptic Patient (VEP). Currently the VEP technology is validated in a large multisite clinical trial EPINOV with 400 prospective epilepsy patients.

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MS118

Data-Driven Identification of Neural Activity Patterns

Firing rates representing neural acitivity are considered which are either directly measured in neuroscience experiments or computed from microscopic Hodgkin-Huxley type of models. Principal neural modes representing macroscopic neural activity patterns are identified from this microscopic data using a diffusion map algorithm. The obtained principal neural modes define a neural manifold, i.e. a low-dimensional representation of the activity. This description helps to analyse the macroscopic dynamics of the system. The approach is developed and tested for experimental data and data gained from a large-scale model of the basal ganglia thalamocortical network respresenting movement disorders and their treatment with deep brain stimulation. Depending on the parameters, the model describes healthy as well as Parkinsonian behaviour. From the properties of the neural manifolds, we extract the spatio-temporal differences characterizing the transition from a healthy to a Parkinsonian state.

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MS119

Experimental Studies of Spiral Wave Teleportation and Applications to Defibrillation

Many chemical and biological systems can sustain complex spiral wave dynamics. In the heart, spiral waves of electrical activity induce deadly arrhythmias and must be eliminated with a large, system-wide perturbation to restore a healthy rhythm. However, the high-energy shocks required for defibrillation therapies are very painful and can even damage heart tissue. In this study, we demonstrate a method for eliminating spiral waves with what should be the minimal possible stimulus required in space for termination. To do this, we show how a localized perturbation can be designed to annihilate simultaneously all spiral waves both free and bound. This identified mechanism is applicable to any excitable system and, for the heart, may lead to more efficient defibrillation strategies.

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MS119

Emergent Hypernetworks with Nonlinearly Coupled Electrochemical Oscillators

Electrochemical oscillators can be coupled through engineered linear and nonlinear feedbacks with time delay. By experimentally measuring the phase dynamics of such oscillators, phase models can be constructed that can predict synchronization patterns as a result of nonlinear coupling due to higher harmonics in the coupling function. Here we show that nonlinear coupling, which is based on pairwise interactions, can be designed to induce hypernetworks, which are dependent on triplet phase difference interactions. An experimental system with a generic network motif with a ring of four electrochemical oscillators is presented, where a relatively simple nonlinear modulation of the coupling induces a hypernetwork driven phase dynamics. The results are interpreted with coupled Stuart Landau oscillators, where the mechanism for emergent hypernetworks is described by identifying appearing and forbidden frequency resonance conditions. The findings open new avenues for hypernetwork based description and engineering of complex systems with heterogeneous frequencies and nonlinear interactions.

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MS119

Mechanisms for Creating Isochron Foliation Tangencies

Basins of attraction of periodic orbits and focus equilibria of vector fields are foliated by forward-time isochrons, defined as the sets of points that synchronise under the flow with a point of a given phase. By considering the time-reversed flow, it follows that basins of repulsion are similarly foliated by backward-time isochrons. Each of these two foliations is transverse to the foliation by trajectories of the respective basin. Yet, in regions where they both exist, the two foliations by forward-time and by backward-time isochrons may not be transverse to each other but feature structurally stable quadratic tangencies, which occur along specific trajectories. Focusing on planar vector fields, we present two ways in which such tangencies may arise as parameters are changed: (i) the cubic isochron foliation tangency; and (ii) the transition through certain global bifurcations. Moreover, we show that isochron foliation tangencies are associated with phase sensitivity and may be an obstacle to phase-based reduction approaches.

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MS119

Experimental Studies of Spiral Wave Teleportation

Experiments are carried out with the photosensitive Belousov-Zhabotinsky (BZ) reaction, which is monitored with a computer interfaced camera and illuminated with a computer-controlled video projector. The wave behavior is studied in a thin layer of silica gel in which the Ru(II) catalyst is immobilized. The gel is cast onto a microscope slide and bathed in a continuously refreshed catalyst-free BZ solution. The video projector and video camera interfaced with a computer allow real-time feedback for perturbing the light sensitive medium and monitoring its response. We demonstrate experimentally that a designed perturbation in time and space can effectively teleport spiral waves across the domain. It is therefore possible to not only control the spiral wave position but also to terminate them at any time.

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MS120

Mathematical Model of Sexual Response

In this talk I will discuss a mathematical model of Masters-Johnson human sexual response cycle. As a starting point, I will review cusp catastrophe and will show why earlier studies that interpreted sexual response cycle using this catastrophe were incorrect. I will then present a derivation of a phenomenological psycho-physiological model of human sexual response cycle. Bifurcation analysis is performed to identify stability properties of the model's steady state, and numerical simulations are performed to illustrated different types of dynamics associated with the cycle. We will then look at the stochastic version of the model, for which the spectrum, variance and coherence of stochastic oscillations around deterministically stable steady state are found analytically, and confidence regions are computed. To make a better understanding of stochastic dynamics, I will show how large deviation theory can be used to compute optimal escape paths from the neighbourhood of the steady state. I will discuss implications of the results for facilitating better quantitative understanding of the dynamics of human sexual response, and for improving clinical practice.

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MS120

The Effects of Delay on the Haken-Kelso Bunz Model of Human Motor Coordination

Understanding human motor coordination holds the promise of developing diagnostic methods for mental illnesses such as schizophrenia. We analyse the celebrated Haken-Kelso-Bunz (HKB) model, describing the dynamics of bimanual coordination, in the presence of delay. We study the linear dynamics, stability, nonlinear behaviour and bifurcations of this model by both theoretical and numerical analysis. We calculate in-phase and anti-phase limit cycles as well as quasi-periodic solutions via double Hopf bifurcation analysis and centre manifold reduction. Moreover, we uncover further details on the global dynamic behaviour by numerical continuation, including the occurrence of limit cycles in phase quadrature and 1-1 locking of quasi-periodic solutions.

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MS120

Imitation Dynamics of Vaccination with Distributed Delay Risk Perception

In this talk I will discuss the dynamics of paediatric vaccination when modelled as a game, where increase in the rate of vaccination is taken to be proportional to the perceived payoff. Similarly to earlier models, this payoff is considered to be a difference between the perceived risk of disease, as represented by its momentary incidence, whereas for the perceived risk of vaccine side effects I will use an integral of the proportion being vaccinated with some delay kernel. This delay distribution can model two realistic effects: the fact that vaccine side effects take some time to develop after a person has been vaccinated, and that even after side effects have appeared, awareness of them will continue to impact vaccination choices for some period of time. I will discuss conditions of feasibility and stability of the disease-free and endemic steady states of the model for the general delay distribution, and for some specific delay distributions that include discrete delay, Gamma distribution (weak and strong cases), and the acquisition-fading kernel. To make the model more realistic, I will also consider the impact of a public health campaign on vaccination dynamics and contrast it to the case where vaccination choices are only dictated by information exchange between vaccinating and non-vaccinating people.

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MS120

Dynamic Parenclitic and Synolitic Network Analysis

Representing high-dimensional biological data in the form of a graph and linking features by biological and thermodynamic laws seems to be a very promising approach to deal with overwhelming complexity of biological systems. However, one can utilise this approach only if we have information about how features and attributes are connected biologically. Here we would like to draw attention to alternative methods to represent high dimensional data in the form of the graph if a-priori we do not have established connections. First of all, correlation-prediction graphs can be used as a marker of survival and have been constructed to represent the gene methylation profiles of individuals. Secondly, there is an algorithm, first described by Zanin and Bocaletti, able to establish links between parameters/nodes without any a-priori knowledge of their interactions using residual distances from linear regression models constructed between every pair of analytes to construct a graph. Thirdly, based on the understanding that the interactions of two features (at least in biological systems) often cannot be described by a linear model, we proposed to use 2-dimensional kernel density estimation to model the control distribution. Finally, we have introduced a variation of parenclitic networks, that can be called synolitic and that can be considered an ensemble of classifiers in a graph form.

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MS121

Enhancing Machine Learning Methods for Cardiac Electrophysiology Through the use of Eikonal Simulations

Machine learning (ML) methods can potentially improve diagnosis in different fields of medicine. Large numbers of clinical data are required to properly train these methods, which are often unavailable in the desired quantity and quality. On the other hand, in silico data can replace or extend clinical data to train ML methods. In three examples, eikonal model simulations were used for this purpose. First, a neural network was trained to quantify the percentage of fibrotic tissue in the atria by using simulated P waves. The fibrosis extent was estimated by a neural network with an absolute root mean square error of 8.78%.

Second, a decision tree classifier with a hold-out classification approach was trained using a hybrid dataset of atrial flutter cases (1424 in silico ECGs and 345 clinical ECGs). The decision tree was able to predict the localization of atrial flutter outperforming previous methods. Finally, in an ongoing project, the eikonal model was combined with biophysical models to simulate complex cardiac arrhythmias more accurately. This method will be used to develop a ML method predicting the arrhythmogenicity of different patterns of fibrosis. These three studies are representative cases of how the eikonal model can be a powerful tool to enable or fuel the application of ML methods in cardiac research.

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MS121

Machine Learning of Spatiotemporal Organization of Electrograms and Clinical Data Predicts Response to Atrial Fibrillation Ablation

This talk will cover approaches to quantify spatiotemporal dynamics of atrial fibrillation (AF) from clinical electrophysiological data such as intracardiac electrograms, patient characteristics etc. Specific focus will be on Machine Learning (ML) of such data to predict outcomes of AF ablation therapy. I will discuss both past studies in the literature and recently published methods such as REpetitive ACTivity (REACT) mapping for AF, which is a novel approach to identify regions of organization in AF atrium. Simulations of morphological and timing variations in AF electrograms showed high robustness of REACT method. Unsupervised Machine Learning of REACT and 50 clinical variables predicted AF termination by ablation. I will conclude with some thoughts on the future of ML for clinical cardiac electrophysiology applications including improving AF ablation outcomes.

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MS121

Creation of Predictive Cardiac Excitation Model at the Tissue Scale with Machine Learning

Electrical wave propagation in cardiac muscle tissue is often modelled as a reaction-diffusion system. The reaction term, the so-called *in silico* tissue model or cell model describes the ion dynamics in, around, and between cells. Tissue models are often fit on the single-cell level using few current or voltage traces from patch clamp recordings and restitution curves, i.e. a small amount of data. In this talk, I outline a novel data-driven approach to create tissue-based models from optical voltage mapping experiments of conditionally immortalized human atrial myocyte monolayers using machine learning. This is done by extracting features from the full spatiotemporal evolution of the optically recorded transmembrane potential. A neural network is then fit to these features. The trained neural network-based models are able to predict the spiral wave propagation even though they are only trained on waves from point sources. This project is one further step towards a fully patient-specific tissue model.

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MS121

Classifying Atrial Tachycardia Dynamics Using Machine Learning

In this talk, we will present a unique topological classification of atrial tachycardia (AT). We will demonstrate that is it possible for each different case to uniquely label the AT, and propose a novel optimal ablation strategy. In a first part, we will show how we extended our software tool, DGM or directed graph mapping, so it can uniquely classify a measured AT. DGM uses network theory to convert the AT into a single network. This network and the topology of the atrium are the building blocks of the classification. In a second part, we will demonstrate the classification with a series of over 1000 different simulations, which will represent a large variety of different ATs. We will show how this classification leads to an optimal ablation target, which is close to 100% successful in case of simulated ATs. In a third part, we will apply our classification on a database of 120 ATs and show that our ablation strategy is superior to the current ablation strategy. Finally, we will demonstrate how machine learning can automatize the classification even further. This research opens future perspectives for the analysis of atrial fibrillation. We will end with some ideas how the classification of AT can lead to a better understanding of AF.

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MS122

Multiscale Modelling of Immunity to Sars-Cov-2

Waning of immunity to Sars-Cov-2 natural infection and vaccination is fundamental to understanding the Covid-19 pandemic. We implement an age structured multi-scale model of the Sars-Cov-2 pandemic to elucidate the distribution of immunity to Sars-Cov-2 in the Canadian province of Ontario over the pandemic. The waning of immunity from natural infection and vaccination is informed from an in-host model of Sars-Cov-2 infection and vaccination. The in-host dynamics are fit with a mixed effects statistical model to a CITF modelling group dataset with Anti-S, Anti-RBD, and Anti-N humoral features as well as Spike-RBD-specific B cell measurements from 151 individuals from M.A. Brockman and Z.L. Brumme.

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MS122

A Dynamical Systems Model of the Immune System and Viral Re-Exposure

Immune reactions involve a two-step process: the first innate immune response is a non-specific chemical response (for example, interferon) to react to invaders and stimulate further immune mediators, and the second adaptive response is the development of specific antibodies to fight infection. Starting with a relatively simple ordinary differential equations model for the immune system, we then simulate repeated viral re-exposure with a discrete impulse to the virus variable. This creates a "flow, then kick dynamical systems map. We explore the coupling of the innate and adaptive immune responses and look for interesting biological stories. Is it possible that repeated exposure to small viral loads can cause undetectable endemic infection? If so, what ratios of viral load to exposure frequency create this behavior? What other possible re-exposure scenarios can we simulate with this type of system?

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MS122

Compartmental Model Suggests Importance of Innate Immune Response to Survival of Respiratory Viral Infection

The pandemic outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) quickly spread worldwide, creating a serious health crisis. The virus is primarily associated with flu-like symptoms but can also lead to severe pathologies and death. We here present an ordinary differential equation model of the intrahost immune response to SARS-CoV-2 infection, fitted to experimental data gleaned from rhesus macaques. The model is calibrated to data from a nonlethal infection, but the model can replicate behavior from various lethal scenarios as well. We evaluate the sensitivity of the model to biologically relevant parameters governing the strength and efficacy of the immune response. We also simulate the effect of both anti-inflammatory and antiviral drugs on the host immune response and demonstrate the ability of the model to lessen the severity of a formerly lethal infection with the addition of the appropriately calibrated drug. Our model emphasizes the importance of tight control of the innate immune response for host survival and viral clearance.

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MS122

Modeling the Dynamics of Alveolar Macrophages and Interferon Gamma During Influenza Infection

Influenza virus infections are a worldwide leading cause of human morbidity and mortality. Understanding the biological mechanisms that cause severe illness could help to find potential effective treatments. A number of studies have shown that alveolar macrophages are depleted during influenza A infection. Some evidence suggests that the depletion is promoted by interferon gamma. To better understand the relation between IFN-γ production and alveolar macrophage depletion, we developed a model that includes the dynamics of virus, alveolar macrophages, and IFN-γ. We calibrated the model to experimental data from mice infected with influenza and then analyzed the model. The results suggest that IFN-γproduction is from at least two sources and that IFN-γ-mediated alveolar macrophage depletion is nonlinear and has distinct contributions from each of the cell sources.

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MS123

Estimation of Dynamical Systems with Sparse Physiological Data

Data assimilation has been used to estimate dynamics of well measured dynamical systems very accurately. However, in the context of human physiology, measurement can come with a diversity of costs, including human costs, and is generally minimized. Additionally, human physiology tends to be complex, oscillatory, and non-stationary, and using data assimilation to estimate dynamical systems from sparsely measured, oscillatory, non-stationary systems is difficult. This talk will focus on model-estimation difficulties that appear for prototypical physiological system, the glucose-insulin system, given sparse data from an intensive care unit. The complexity of the dynamics of learning will be highlighted, including a problem that has been particularly vexing: the induced mismatch between generating dynamics and inferred-model dynamics. The talk will conclude with solutions to these problems.

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MS123

Sequential Learning in the Context of Optimal Treatment

Model-informed precision dosing (MIPD) leverages prior knowledge and biomarker data for individualized drug dosing. Such dose adjustments are particularly important in fields like oncology, with narrow therapeutic windows and severe dose-limiting effects such as neutropenia. MIPD approaches have been proposed in this field but estimating model parameters can be a crucial factor in describing the personalized trajectories of individual patients. Furthermore, it might be necessary to choose control parameters that can be understood as decisions/actions performed related to the specific therapeutic treatment of a patient. Advanced machine learning techniques in the form of reinforcement learning (RL) have been successfully applied to overcome the computational challenges of deriving optimal treatment plans personalized to individual patients. RL can be described as a set of decision-making rules that allow learning actions to take in specific situations/states by relying on an evaluation of the consequences of these actions. However, standard methods for parameter estimation in RL fail when the dimension of the parameter space becomes large, e.g. in the same or possibly larger order than the sample size. Our objective is to introduce deep reinforcement learning (DRL) to extend a previously proposed RL approach to account for efficient parameter estimation and dose regime optimization in the context of MIPD.

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MS123

A Cerebral Hemodynamic Model with Temporally Informed Vascular Regulation Processes to Guide Clinical Decision Support

A primary goal in neurocritical care is to predict and maintain adequate cerebral blood flow and intracranial pressure. Therefore, it would be clinically efficacious to forecast cerebral hemodynamics. However, the cerebral hemodynamic system comprises multiple vascular feedback mechanisms operating on disparate spatial and temporal scales and confounding simple cerebral blood flow modeling. These vascular feedback mechanisms can become dysfunctional, and it would be clinically and scientifically beneficial to know the state of these feedback mechanisms. In this talk, we present a new model that describes a cerebral hemodynamic system with temporally informed vascular feedback mechanisms as a system of coupled ordinary differential equations. The functionality associated with different vascular feedback mechanisms and the metabolic state of the brain are modeled as inferable parameters that may be used to guide clinical decision support. We then use dynamic systems techniques to explore different regimes of behavior in this hemodynamic model and speculate how these regimes may be interpreted in the clinical setting.

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MS123

Delay-Induced Uncertainty: Is DIU Pathogenic?

We have recently shown that physiological delay can induce a novel form of sustained temporal chaos we call delay-induced uncertainty (DIU) (Karamched et al. (Chaos, 2021, 31, 023142)). This talk assesses the impact of DIU on the ability of the glucose-insulin system to maintain homeostasis when responding to the ingestion of meals. We address two questions. First, what is the nature of the DIU phenotype? That is, what physiological macrostates (as encoded by physiological parameters) allow for DIU onset? Second, how does DIU impact health? We find that the DIU phenotype is abundant in the space of intrinsic parameters for the Ultradian glucose-insulin model, a model that has been successfully used to predict glucose-insulin dynamics in humans. Configurations of intrinsic parameters that correspond to high characteristic glucose levels facilitate DIU onset. We argue that DIU is pathogenic for obesity and type-2 diabetes mellitus by linking the statistical profile of DIU to the glucostatic theory of hunger.

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MS124

Self-Consistent Dynamics of Charged Particles As An Active Mixing Problem

In recent years there has been a growing interest in the study of active mixing, generically defined as transport that deviates from the passive mixing paradigm. Typical examples include reaction-fronts and self-propelled tracers. Going beyond these important problems, in this presentation we consider the dynamics of charged particles in electromagnetic fields from the perspective of active mixing. In the simplest setting charged particle motion can be viewed as a passive transport problem by assuming the electromagnetic fields as externally given. However, this approximation ignores the fact that charge particles, while moving, generate their own electromagnetic fields (according to Maxwells equations) and thus actively modify the background flow. This is the well-known self-consistent dynamics problem of significant interest to plasma physics. To study this problem, we consider a mean-field-coupled Hamiltonian dynamical system that describes the active chaotic mixing of charged particles in a self-consistent wave field. We will also discuss analogies between different levels of approximations of particle orbits in magnetized plasmas and active mixing problems. In the simplest approximation, charge particles simply follow the background flow defined by the magnetic field. However, more accurate, higher order approximations introduce departures from the magnetic field conceptually analogous to the departures from the background flow in non-passive traces in fluids.

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MS124

Swimming the Chaotic Seas: Invariant Manifolds, Tori, and the Transport of Swimmers in Fluid Flows

We analyze the kinematics of micro-swimmers in an imposed microchannel flow consisting of alternating fluid vortices. These swimmers could be biological (e.g. bacteria or algae) or artificial (e.g. Janus particles). Using dynamical systems techniques, we show that transport from one vortex down the channel to another vortex is mediated by both invariant tori and so-called Swimming Invariant Manifolds (SwIMs); SwIMs have previously been emphasized as one-way barriers to swimmer transport, but they also form chutes which guide swimmer passage between vortices. The SwIM geometry thus plays a critical role in determining transport rates of swimmers between vortices. The invariant tori, on the other hand, lead both to trapping within vortex cells and ballistic transport between vortex cells. Both phase space structures thus affect long-time and long-range transport of micro-swimmers. Our theoretical framework is applied to experiments on algae in microfluidic channels.

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MS124

Experimental Studies of Active Mixing of Swimming Microbes and Reaction Fronts in Laminar Flows

We present experiments on the effects of imposed, two-dimensional, laminar flows on the motion of self-propelled tracers and propagating reaction fronts. The self-propelled particles are bacteria (bacillus subtilis) and motile eukaryotic microbes (tetraselmis and euglena), and the propagating reaction are fronts of the excitable Belousov-Zhabotinsky chemical reaction. The flows studied are (a) a hyperbolic flow in a PDMS cross channel, driven by syringe pumps; and (b) both ordered and disordered vortex-dominated flows driven magnetohydrodynamically. The trajectories of the swimming microbes in the flows are analyzed in terms of a theory of “swimming invariant manifolds’ (SwIMs). These SwIMs separate trajectories into distinct regions in a three-dimensional phase space determined by the x and y coordinates and swimming directions of the microbes. Projected into physical, x-y space, the edges of the SwIMs act as one-way barriers through which the active tracers can cross in one-direction only. This theory is a generalization of a theory of “burning invariant manifolds’ (BIMs) that have previously been shown to act as one-way barriers that block the motion of propagating reaction fronts in laminar flows. The SwIMs also combine to produce “chutes’ that carry microbes between adjacent vortices. We measure the growing variance of an ensemble for different microbe swimming speeds and interpret those results in terms of the SwIM geometry.

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MS124

Active Particles in Confined Environments

We consider active particles (microswimmers) moving in an environment with obstacles. These are treated using the Active Brownian Particle model (ABP), where particles move forward at constant speed but in a randomly-varying direction. The goal is to estimate the effective diffusivity of particles in a lattice of obstacles. We use a technique pioneered by Keller in the limit where the environment contains small gaps through which the particle has to squeeze through.

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MS125

Heat Transport in Convection Due to Internal Heating

Understanding convection is an endeavour to understand the transport in fluids on geophysical scales. Buoyancy due to chemical concentration differences is crucial to the dynamics in the ocean and in the Earths core, while buoyancy due to thermal variation drives atmospheric and mantle physics. The scales involved in these environments lead directly to turbulent and chaotic motion, such that finding a solution to the governing equations or simulating the flow numerically are as yet unable to guarantee a holistic view of the dynamics. To gain a deep understanding of the turbulence, it is insightful to look at the long-time behaviour of the emergent properties of the flow, like thermal dissipation or convective heat flux. Convection driven by internal heating is one such simple scenario to investigate buoyancy, wherein a fluid is heated uniformly inside the domain. We look to bound the mean convective heat flux in internally heated convection under different thermal and velocity boundary conditions. Rigorous scaling laws are proven for the heat transport with respect to a Rayleigh number, quantifying the destabilising effect of internal heating to that of diffusion. Rigorous bounds are obtained with the use of the background method, where in contrast to Rayleigh-Bénard convection the thermal boundary conditions change the asymptotic scaling of the convective heat transport with the thermal forcing.

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MS125

Superstructures in Fixed-Flux Rayleigh-Bnard Convection

Rayleigh–Bnard convection is most often modeled with either temperatures or heat fluxes fixed at the boundaries. Three-dimensional simulations by Vieweg, Scheel and Schumacher (Phys. Rev. Res. 3, 013231, 2021) in the regime of strong convection show that superstructures much wider than the domain's height will aggregate in the case where heat fluxes are fixed at the boundaries. We report on two-dimensional simulations with heat fluxes fixed at the boundaries. After confirming the existence of domain-filling superstructures in the two-dimensional case, we explore the parameter space of the Rayleigh number and Prandtl number in a way that would be prohibitively expensive with three-dimensional simulations, identifying a large parameter region in which domain-filling superstructures can be found.

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MS125

Heat Transfer in the Lorenz-Stenflo System

The Lorenz-Stenflo system is a 4-dimensional ODE modeling fluid flow in a periodic box which is heated from below and cooled from above. The temperature gradients induce a buoyancy force, tending to produce a convective flow. This system differs from the classical Lorenz 63' model in that the fluid is now assumed to lie in a rotating frame, so one must also account for the relevant Coriolis force. The question arises how much heat is transported by the fluid from the bottom of the box to the top. The quantity of interest is then the Nusselt number, defined as the average vertical heat flux in the box, averaged also over infinite time. The possible values of heat transport are entirely determined by the invariant structures of the Lorenz-Stenflo evolution, which depend carefully on the physical parameters. Past studies indicate analogous invariant structures to the Lorenz 63 evolution for low rotation, whereas for high rotation different behavior can occur. However, past works have investigated these structures numerically, leaving questions unsettled analytically.

In this talk, I present analytical results about the invariant structures of the Lorenz-Stenflo evolution, and the implications for the heat transport. In parameter regimes where the global dynamics are too complicated to fully settle, I present heat transport values corresponding to nontrivial basins of attraction and upper bounds which can be analytically proven.

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MS126

Simple Hopf bifurcations in reaction networks that admit a monomial parameterization

The dynamics of biochemical reaction networks can be described by ODEs with polynomial right hand side. In this presentation networks are considered where the steady state variety can be parameterized by monomials. Such a parameterization has been established for several network motifs that occur frequently in intracellular signal transduction. By combining this parameterization with results from Liu (1994) and Yang (2002) one can derive polynomial inequality conditions for the existences of simple Hopf bifurcations. This idea has been successfully applied to several network motifs and parameter inequalities that guarantee a simple Hopf bifurcation have been derived. In particular, for a network describing the cyclic and distributive phosphorylation of a protein at two binding sites, an inequality guaranteeing a simple Hopf bifurcation has been derived. This inequality involves only the four catalytic constants (i.e. the catalytic constants of the kinase and the un- and mono-phosphorlyated protein as well as those of the phosphatase and the double- and monophosphorylated protein). Interestingly, for sequential distributive double phosphorylation a similar inequality involving the very same rate constants has been described

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MS126

Source-Only Realizations, Weakly Reversible Deficiency One Networks and Dynamical Equivalence

Reaction networks can display a wide array of dynamics. However, it is possible for different reaction networks to display the same dynamics. This phenomenon is called dynamical equivalence and makes network identification a hard problem. We show that to find a strongly endotactic/endotactic/consistent/conservative realization that is dynamically equivalent to the mass-action system generated by a given network (when it exists), it suffices to consider only the source vertices of the given network. We also present a characterization of the dynamical relationships that exist between several types of weakly reversible deficiency one networks.

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MS126

Graph-Theoretical Conditions for Multistationarity in Mass-Action Reaction Networks

The DSR Theorem due to Banaji and Craciun gives an elegant necessary condition for the existence of multiple positive steady states (multistationarity) of a reaction network. Their result depends only on the structure of the network, and extends and refines the famous “Thomas conjecture” stating that positive feedbacks are necessary for multistationarity. We present a partial converse to the DSR Theorem and show that the existence of cycles with certain properties in the DSR graph of a mass-action network guarantees that the network has the capacity for multistationarity. Our result relies on lifting steady states from subnetworks and on the recent classification of multistationarity for the class of CST (cyclic sequestration-transmutation) networks.

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MS126

Dynamics of GPCR Signalling

G-protein coupled receptors (GPCRs) is a class of transmembrane receptors important to many signalling pathways and a common drug target. Such a receptor, when activated by a ligand, binds to and activates a G-protein, which then goes on to induce downstream signalling. The reaction network for G-protein activation is also incredibly simple, so it is surprising that only 4 classes of G-proteins are involved in hundreds of pathways. In this talk I will present a model of G-protein activation, and consider what its dynamics mean for GPCR signalling in general.

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MS127

Synchronization of Phase Oscillators on Complex Hypergraphs

Recent studies have highlighted the prevalence of higher order interactions in various complex systems and how they can modify the collective dynamics that are observed only when pairwise interactions are present. We study the effect of structured higher-order interactions on the synchronization behavior of the coupled phase oscillators. By combining hypergraph generative model with dimensionality reduction techniques, we develop mean-field analysis and obtain a reduced system of differential equations for the systems order parameters. We illustrate our framework with two hypergraphs with hyperedges of size 2 (links) and 3 (triangles). For strong values of coupling via triangles, the system exhibits bistability of the incoherent and synchronized states, and explosive synchronization transitions. We find the conditions for synchronization and bistabilility in terms of hypergraph properties and validate the predictions with numerical simulations. Our results provide a general and flexible framework to study synchronization on complex hypergraphs and can be extended to hypergraphs with hyperedges of arbitrary sizes, dynamic-structural correlations, and other features.

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MS127

Enlarged Kuramoto Model: Collective Chaos Induced by Higher-Order Interactions

The emergence of collective synchrony from an incoherent state is a phenomenon essentially described by the Kuramoto model. This canonical model was originally derived in a perturbative way, from an ensemble of heterogeneous, globally coupled Stuart-Landau oscillators. The derivation, via phase reduction, only considered terms up to linear order in the coupling constant. In this contribution, we show that a comprehensive analysis requires extending phase reduction up to quadratic order. The resulting "enlarged Kuramoto model" comprises higher-order (triadic) interactions, which induce strikingly complex phenomenology at certain parameter values. As the coupling is increased, a secondary instability renders the synchronized state unstable, and subsequent bifurcations lead to collective chaos and hyperchaos. These results clarify the nature of certain complex dynamics observed in the ensemble of Stuart-Landau oscillators.

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MS127

Cluster Synchronization on Hypergraphs

Full synchronization of dynamical elements coupled via hypergraphs can be analyzed with the hypergraph projection onto dyadic matrices, but this is not sufficient for analyzing cluster synchronization. Here we present an analysis formulated in terms of node clusters and edge clusters. This allows us to verify admissible states of cluster synchronization on hypergraphs and simplify their linear stability calculations by using the projected Laplacian matrices based on each edge cluster. This provides a principled way to track dynamics on hypergraphs. This work goes beyond full synchronization and beyond dyadic interactions.

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MS127

Hypergraphs Or Simplicial Complexes: Untangling the Effect of Higher-Order Representations on Collective Dynamics

Higher-order networks have emerged as a powerful framework to model complex systems and their collective behavior. Going beyond pairwise interactions, they encode structured relations among arbitrary numbers of units through representations such as simplicial complexes and hypergraphs. So far, the choice of the representation has often been motivated by technical convenience. In this talk, using synchronization of coupled oscillators, I will demonstrate that the effects of higher-order interactions are highly representation-dependent. In particular, hyperedges typically enhance synchronization in hypergraphs, but have the opposite effect in simplicial complexes. I will further explain this result by analytically linking higher-order representation to (generalized) degree heterogeneity, which in turn influences a wide range of dynamical processes from contagion to diffusion. This finding reveals the hidden impact of higher-order representations on collective dynamics and highlights the importance of choosing appropriate representations when describing systems with nonpairwise interactions.

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MS128

Patterns in Wildfire Fronts

The emergence of counter-rotational vortices in the velocity fields generated by both wildland fires and laboratory-scale experimental fires is a well-documented but relatively poorly understood phenomenon. The structures formed by these vortices, sometimes called towers and troughs, are an important mechanism of heat transfer in flaming fires. A deeper understanding and mathematical description of the physical mechanisms underlying the formation of these structures would aid in the development of faster, more accurate models of fire spread. We hypothesize that towers and troughs emerge as a result of thermally driven buoyancy and independent of fuel consumption, a theory supported by previous experimental work. When viewed this way, the formation of counter-rotational vortices looks very similar to the formation of convective cells in Rayleigh-Bnard convection. To exploit this analogy, we formulate the Boussinesq equations for fluid flow over a hot plate in a moving frame corresponding to a constant horizontal wind velocity and analyze the instabilities that emerge in the resulting system of PDEs.

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MS128

Fractals and Multiscale Pattern Formation in Earth's Sea Ice System

Sea ice is a multiscale composite that displays fascinating geometry on length scales that range over many orders of magnitude. Tiny brine inclusions inside the sea ice, melt ponds on the sea ice surface, the ice pack itself, and even the marginal ice zone on the scale of the Arctic Ocean all exhibit fractal geometry and beautiful pattern formation dynamics. We will discuss the mathematics of these multiscale structures, and their role in Earth's climate system.

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MS128

Surface Meltwater Pattern Formation by Flexural Wave Excitation of Ice Shelves

Surface meltwater production is often the proximal cause of ice shelf instability. While much of this meltwater is drained by supraglacial streams, standing meltwater can self-organize to form remarkable patterns, like the zebra stripes found on the Ellesmere Ice Shelf and the en echelon lakes found on the George VI Ice Shelf. In this work, we present an idealized model of meltwater patterning caused by periodically forced vibrations of the ice shelf. Using modified shallow-water equations on a moving bed, we explore the surface hydrology above an ice shelf forced to oscillate by ocean waves. We demonstrate that standing flexural-gravity waves may create and maintain meltwater features which correspond to Faraday wave modes. Understanding the spatial dynamics of meltwater will be crucial for predicting ice shelf instability in a warming climate.

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MS128

Brine Inclusions in First-Year Sea Ice

The freezing of salt water engenders phase separation into ice and salt rich brine. The ejection of the salt from the ice phase and its concentration within the liquid is a form of chemotaxis. We present a thermodynamically self-consistent model, built upon the GENRIC framework introduced by Mielke and earlier work of Penrose and Fife. We derive a slow system for the evolution of the brine-ice interface, and present simulations that show that the thermal gradient in sea ice, from the cold top layer to the warmer bottom, induces spherical inclusions to migrate and tubular inclusions to pinch off into smaller spherical ones.

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MS129

Variational Quantum Solutions to the Burgers' Equation for Applications in Fluid Dynamics

Constraints in power consumption and computational power limit the skill of operational numerical weather prediction by classical computing methods. Quantum computing could potentially address both of these challenges. Herein, we present one method to perform fluid dynamics calculations that takes advantage of quantum computing. This hybrid quantum-classical method, which combines several algorithms, scales logarithmically with the dimension of the vector space and quadratically with the number of nonzero terms in the linear combination of unitary operators that specifies the linear operator describing the system of interest. As a demonstration, we apply our method to solve the Burgers' equation for a small system using IBM quantum computers. We find that reliable solutions of the equation can be obtained on even the noisy quantum computers available today. This and other methods that exploit quantum computers could replace some of our traditional methods in numerical weather prediction as quantum hardware continues to improve.

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MS129

Quantum Algorithm for Simulating Stochastic Nonlinear Dynamical Systems

Quantum algorithms have been developed to solve sparse linear ODEs in time proportional to poly(log(n)) using the quantum linear systems algorithm (QLSA), where n is the dimensionality of the phase space. The natural extension of this approach to nonlinear ODEs involves linearization using techniques such as Carleman linearization and Koopman von Neumann approaches among others. In this work, we discuss an efficient quantum algorithm for solving nonlinear stochastic differential equations (SDE) via the associated Fokker-Planck equation (FPE). We discretize FPE in space and time using the Chang-Cooper scheme, and compute the solution of the resulting system of linear equations using the quantum linear systems algorithm. The Chang-Cooper scheme is second order accurate and satisfies conservativeness and positivity of the solution. We present the error and complexity estimates and demonstrate that our proposed quantum scheme provides an exponential speed-up over traditional approaches.

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MS129

Efficient Quantum Algorithm for Solving Nonlinear Differential Equations with Polynomial Vector Fields of Arbitrary Degree

We present an efficient quantum algorithm to simulate nonlinear differential equations with polynomial vector fields of arbitrary degree on quantum platforms. Models of physical systems that are governed by ordinary differential equations (ODEs)/partial differential equation (PDEs) arise extensively in science/engineering applications and can be challenging to solve on classical computers due to high dimensionality, stiffness, and nonlinearities. For sparse n-dimensional linear ODEs, quantum algorithms have been developed which produce a quantum state proportional to the solution in time which is polynomial in log(n) using the quantum linear systems algorithm (QLSA). Recently, this framework was extended to nonlinear ODEs with quadratic polynomial vector fields by applying Carleman linearization. A detailed complexity analysis showed significant computational advantage under certain conditions. We present an extension of this algorithm to deal with nonlinear ODEs with k-th degree polynomial vector fields for arbitrary (finite) values of k. The steps involve: 1) mapping the k-th degree polynomial ODE to a higher dimensional quadratic polynomial ODE; 2) applying Carleman linearization to transform the quadratic ODE to an infinite-dimensional system of linear ODEs; 3) truncating and discretizing the linear ODE and solving using the forward Euler method and QLSA. We present a detailed complexity analysis of the proposed algorithm and demonstrate it on numerical examples.

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MS129

Efficient Quantum Algorithm for Dissipative, Weakly Nonlinear Differential Equations

Nonlinear differential equations model diverse phenomena but are notoriously difficult to solve. While there has been extensive previous work on efficient quantum algorithms for linear differential equations, the linearity of quantum mechanics has limited analogous progress for the nonlinear case. Despite this obstacle, we develop a quantum algorithm for dissipative quadratic n-dimensional ordinary differential equations. Assuming R ¡ 1, where R is a parameter characterizing the ratio of the nonlinearity and forcing to the linear dissipation, this algorithm has complexity polynomial in T, where T is the evolution time. This is an exponential improvement over the best previous quantum algorithms, whose complexity is exponential in T. While exponential decay precludes efficiency, driven equations can avoid this issue despite the presence of dissipation. Our algorithm uses the method of Carleman linearization, for which we give a novel convergence theorem. This method maps a system of nonlinear differential equations to an infinite-dimensional system of linear differential equations, which we discretize, truncate, and solve using the forward Euler method and the quantum linear system algorithm. We also provide a lower bound on the worst-case complexity of quantum algorithms for general quadratic differential equations, showing that the problem is intractable for $R \geq \sqrt{2}$. Finally, we discuss potential applications in epidemiology and fluid dynamics related problems.

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MS130

Spatio-Temporal Heterogeneities in a Mechano-Chemical Model of Collective Cell Migration

Small GTPases, such as Rac and Rho, are well known central regulators of cell morphology and motility, whose dynamics also play a role in coordinating collective cell migration. Experiments have shown GTPase dynamics to be affected by both chemical and mechanical cues, but also to be spatially and temporally heterogeneous. This heterogeneity is found both within a single cell, and between cells in a tissue. For example, sometimes the leader and follower cells display an inverted GTPase configuration. While progress on understanding GTPase dynamics in single cells has been made, a major remaining challenge is to understand the role of GTPase heterogeneity in collective cell migration. Motivated by recent one-dimensional experiments (e.g. micro-channels) we introduce a one-dimensional modelling framework allowing us to integrate cell bio-mechanics, changes in cell size, and detailed intracellular signalling circuits (reaction-diffusion equations). Using this framework, we build cell migration models of both loose (mesenchymal) and cohering (epithelial) tissues. We use numerical simulations, and analysis tools, such as local perturbation analysis, to provide insights into the regulatory mechanisms coordinating collective cell migration. We show how feedback from mechanical tension to GTPase activation lead to a variety of dynamics, resembling both normal and pathological behavior.

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MS130

Nonlocal Continuum Models of Cell-Cell Adhesion and Their Cahn-Hilliard Approximation

Cell-cell adhesion is one the most fundamental mechanisms regulating collective cell migration during tissue development, homeostasis and repair, allowing cell populations to self-organize and eventually form and maintain complex tissue shapes. Adhesive forces are highly linked to the cell geometry and often, continuum models represent these by nonlocal attractive interactions. In this talk, I will explain how such models can be approximated by Cahn-Hilliard type equations in the limit of short-range interactions. The resulting model is local, resembling a thin-film type equation, and numerical simulations in one and two dimensions reveal that it still shows the diversity of patterns observed both in experiments and in previously used nonlocal models. In addition, it also has the advantage of having explicit stationary solutions, which provides a direct link between the model parameters and the differential adhesion hypothesis.

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MS130

Why Does It Form a Heart Shape? A Vertex Model

of Meristem Formation in Ferns

During one stage of the life cycle of the fern Ceratopteris richardii, the plant takes the form of a gametophyte, a flat collection of a few hundred cells. Over the course of a couple of days, this gametophyte transitions from roughly circular to a heart shape. In the notch region of the heart, stem-cell like tissue continuously generates new cells that impact the morphology of the plant. If this tissue is removed, the fern restructures and dynamically develops a new notch. To better understand this process, we build a vertex dynamics model that describes the shape and position of individual cells. Our model accounts for observations that the cell division rate is position-dependent rather than lineage-dependent, and we quantitatively compare our simulations with in vivo results.

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MS130

Weak-Form Equation Learning for Interacting Particle System Models of Collective Motion

Interacting particle systems (IPS) have proven to be highly successful in describing the spatial movement of organisms. However, it is challenging to infer the interaction rules directly from data. In the field of equation discovery, the Weak form Sparse Identification of Nonlinear Dynamics (WSINDy) methodology has been shown to be computationally efficient for identifying the governing equations of complex systems from noisy data. Motivated by the success of IPS models to describe the spatial movement of organisms, we develop WSINDy for inference of 1st-order and 2nd-order IPS models. In the 1st-order case, we leverage mean-field theory to infer interaction rules in the population-level setting by means of associated nonlocal PDEs. For 2nd-order models, we consider possibly heterogeneous interaction rules, varying between individuals, and we develop a joint model selection and classification method to both learn governing IPS equations and sort individuals into distinct interaction rule classes. In particular, we learn an ensemble of models each from individual trajectories, and iteratively use suitable ensemble-averaged models to classify individuals into distinct classes. We demonstrate the efficiency and proficiency of these methods on several test scenarios, motivated by common cell migration experiments.

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MS132

Continuous Data Assimilation: Insights & Connections to Understanding Turbulent Flows

One of the challenges of the accurate simulation of turbulent flows is that initial data is often incomplete, which is a significant difficulty when modeling chaotic systems whose solutions are sensitive to initial conditions. If one instead has snapshots of a system, i.e. data, one can make a better guess at the true state by incorporating the data via data assimilation. Many of the most popular data assimilation methods were developed for general physical systems, not just turbulent flows or chaotic systems. However, in the context of fluids, data assimilation works better than would be anticipated for a general physical system. In particular, turbulent fluid flows have been proven to have the property that, given enough perfect observations, one can recover the full state irrespective of the choice of initial condition. This property is unique to turbulent fluid flows, a consequence of their finite dimensionality. In this presentation, we will discuss the continuous data assimilation algorithm that was used to prove the convergence in the original, perfect data setting, present various robustness results of the continuous data assimilation algorithm, and discuss how continuous data assimilation can be used to identify and correct model error. Moreover, we will highlight the efforts of our other current research into long-standing problems in the stability of fluid flows, and how we have discovered some very interesting connections to our data assimilation research.

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MS132

Reconstructing External Forces in Hydrodynamic Equations

We describe a variation of a "spectral filtering" approach originally developed by Celik, Olson, and Titi 2019 in order to recover the unobserved high-mode motion of the flow provided that sufficiently many low-modes are observed and that the external force is known. We apply this idea to simultaneously reconstruct the unobserved motion in addition to an apriori unknown external force in the 2D Navier-Stokes equations

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MS132

Accelerated Convergence of Solvers Through Continuous Data Assimilation

We show how continuous data assimilation (CDA) can be used to improve nonlinear solvers for steady PDEs. For incompressible flows, we show how CDA can provide for improved linear convergence in Picard iterations, and can increase the radius of convergence in Newton iterations. Numerical tests are given that illustrate the theory.

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MS132

Improving Convergence Rates for Continuous Data Assimilation with Sparse-In-Time Observational

Data

In this talk we consider an algorithm for continuous data assimilation for sparse-in-time observational data. We show that by assimilating the observational data only in a small time window after the observations were made allows us to increase the strength of the nudging parameter which greatly increases the rate of convergence to the true solution. We show computational tests with our algorithm on the 3D incompressible Navier-Stokes equations where we yield an order-of-magnitude improvement over the algorithm proposed by Foias, Mondaini, and Titi in 2016.

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MS133

How Higher Order Interactions Shape the Dynamics of Hypernetworks

Many real-world interconnected systems are governed by non-pairwise interactions between agents frequently referred to as higher order interactions. The resulting higher order interaction structure can be encoded by means of a hypergraph or hypernetwork. This talk will focus on dynamics of such hypernetworks. We define a class of maps that respects the higher order interaction structure, so-called admissible maps, and investigate how robust patterns of synchrony can be classified. Interestingly, these are only defined by higher degree polynomial admissible maps. This means that, unlike in classical networks, cluster synchronization on hypernetworks is a higher order, i.e., nonlinear effect. This feature has further implications for the dynamics. In particular, it causes the phenomenon of “reluctant synchrony breaking’ on hypernetworks, which occurs when bifurcating solutions lie close to a non-robust synchrony space.

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MS134

Modeling Dengue Immune Responses Mediated by Antibodies: Insights on the Immunopathogenesis of Severe Disease

With more than one-third of the world population at risk of acquiring the disease, dengue fever is a major public health problem. Caused by four antigenically distinct but related serotypes, disease severity is associated with the immunological status of the individual, seronegative or seropositive, prior to a natural dengue infection. While a primary natural dengue infection is often asymptomatic or mild, individuals experiencing a secondary dengue infection with a heterologous serotype have higher risk of developing the severe form of the disease, linked to the antibody-dependent enhancement (ADE) process. We develop a modeling framework to describe the dengue immune responses mediated by antibodies. Our model framework can describe qualitatively the dynamic of the viral load and antibodies production for scenarios of primary and secondary infections, as found in the empirical immunology literature. Studies such as the one described here serve as a baseline to further model extensions. Future refinements of our framework will be of use to evaluate the impact of imperfect dengue vaccines.

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MS134

Recent Advances in the Analysis of Longitudinal Cancer Biomarkers

Despite recent advances in the development of approaches for earlier detection and treatment, multiple malignancies still have very poor prognosis. One of the approaches suggested to improve the predictive performance of biomarker-based machine learning methods is to incorporate changes in longitudinal biomarkers rather than consider measurements at single time points. Over the last years we have developed the MMT (method of mean trends) algorithm for the analysis of serial patterns in single or multiple biomarkers as well as tested a number of existing approaches. The latter included Bayesian change point modelling, parametric empirical bayes (PEB) as well as various recurrent neural networks architectures (RNN). Performance was evaluated as area under the ROC-curve (AUC) as well as the value of sensitivity at fixed clinically justified specificity. Using the example of ovarian cancer, we have definitively shown that longitudinal analysis significantly outperforms the performance of current best biomarkers measured at single time. This has been observed for all the machine learning methods that we have evaluated. We have also seen that a combination of longitudinal biomarkers may outperform single longitudinal parameters, this in particular has been observed for CA125+HE4 model compared to CA125 only in ovarian cancer. Analysis of individual patterns in biomarker levels may allow higher cancer detection rates and earlier detection.

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MS134

Analysis of and Dynamics on the Multi-Layer Network of C. Elegans

The nematode Caenorhabditis elegans (C. elegans) is a model organism to demonstrate the power of dynamical systems on networks, because its connectome and physiology are well documented. In this presentation, I will summarize recent results on this complex system. First, I will discuss how synchronization patterns and chimera-like states emerge in the Hindmarsh-Rose equations for neuronal activity on the modular multi-layer topology that reflects the electrical, chemical, and (putative) wireless coupling between neurons. Then, I will present how locomotory behavior can be modeled by combining neuronal and muscular activity patterns that control forward locomotion. For this purpose, the neuronal equations are augmented by a leaky integrator model for muscular activity. The dynamics of the forward locomotion of the worm is inferred based on a harmonic wave model. In addition, the application of time-delayed feedback control reveals synchronization patterns that contribute to a coordinated locomotion of C. elegans.

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MS134

Simulation of Neuroimaging Data by Whole-Brain Dynamical Models

Resting-state brain dynamics measured by the functional magnetic resonance imaging (fMRI) can effectively be modeled by the 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 (SC) and functional (FC) brain connectivity, respectively. The modeling results however exhibit a pronounced variability across individual subjects and brain parcellations used to delineate the brain into a network of brain regions serving as an underlying structure of the models. We investigate the inter-subject and inter-parcellation variability and show that it can well be accounted for by a few data variables calculated from the empirical neuroimaging data used for the model derivation and validation. We further demonstrate that the reliability and subject specificity of the simulated FC can exceed those of the empirical one depending on the considered brain atlas and in spite of the observed inter-subject variability, especially, for the personalized models. The obtained results therefore suggest an application of the whole-brain models to behavioral and clinical data, for example, to classification of patients and healthy controls.

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MS135

Deep Learning Discrete-Time Bifurcations: An Application to Noisy Cardiac Systems

Many processes in nature, such as the (ar)rhythmic beating of cardiac systems, are well described by discrete-time dynamical systems. Bifurcations in these systems can result in a sudden, potentially devastating shift in dynamics. In this talk, I will demonstrate how deep learning can help predict these bifurcations. The approach involves training a deep learning classifier on a 'universe' of different bifurcation trajectories, generated using normal form models with random higher-order terms. We find that the classifier can successfully predict period-doubling bifurcations in experimental data of chick heart aggregates, and can distinguish between several types of local bifurcation in model simulations. I argue that deep learning as a tool for bifurcation prediction is still in its nascence and has the potential to transform the way we monitor systems for phase transitions.

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MS135

Tipping Points, Critical Transitions, and Bifurcations in Biology: Can We Predict the Future?

In a 2009 Nature Reviews Article, Marten Scheffer and colleagues made bold claims. "Complex dynamical systems, ranging from ecosystems to financial markets and the climate, can have tipping points at which a sudden shift to a contrasting dynamical regime may occur. Although predicting such critical points before they are reached is extremely difficult, work in different scientific fields is now suggesting the existence of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching." I will discuss early work in catastrophe theory and bifurcation theory that provided the mathematical foundations for these claims. I will also describe concrete applications to experimental systems, as well as potential applications in medicine. As will be described in subsequent talks in the mini-symposium Phase transitions in electrophysiological systems recent work is focusing on the possibility of predicting the onset pathological conditions, such as cardiac arrhythmia and epileptic seizures, by combining mathematical insights of bifurcations in stochastic systems in the neigborhood of a bifurcation point with artificial intelligence analysis of large data sets collected noninvasively.

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MS135

Numerical Continuation Approaches for Computing Phase Response in Higher-Dimensional Models: Isochrons of the Hodgkin-Huxley Model

Phase resetting concerns how the phase of an oscillator shifts in response to a fixed perturbation applied at a given moment in its cycle and with a given amplitude. Such information can determine how clusters of oscillators synchronize, which underlies the function or failure of many biological systems. One can study phase resetting via the arrangement of the isochrons of the periodic orbit. These are (n-1)-dimensional sub-manifolds in the basin of attraction, formed as the points that converge to the periodic orbit with the same specific phase. While methods exist to compute isochrons in systems of two- and even three-dimensions, computing and visualizing isochrons of higher-dimensional systems is a challenge. We present an approach via the continuation of a multi-segment two-point boundary-value problem, to evaluate the consequent phase of points perturbed away from the oscillator. The set of perturbed points forms a two-dimensional space parametrized by perturbation amplitude and application phase. As well as allowing for the computation of the classic phase response curve, segments of isochron that intersect this two-dimensional space can be computed directly as one-dimensional curves. To illustrate our method, we consider the four-dimensional Hodgkin-Huxley model, and present isochrons that correspond to phase resetting with an instantaneous perturbation, and also with a time-varying perturbation.

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MS136

Robust Oscillations Against Spatial-Temporal Noise in Intra-Inter Cellular Kinetics

The circadian clock generates 24h rhythms every day via a negative feedback loop. Although this involves the daily entry of molecules to the nucleus after random diffusion through a crowded cytoplasm, the period is extremely well preserved. Furthermore, the period is well maintained across the cell population whose size differs considerably. In this talk, I will illustrate how thousands of molecules work together via phosphoswitch in time and space to compensate for their spatio-temporal variations and maintain robust rhythms, which we identified using the combination of agent-based modeling and single-cell imaging experiments. Furthermore, when cells become too crowded for the phopshoswitch to function, circadian rhythms become unstable. Follow-up in vivo experiments showed that mice having either obesity, autophagy mal-function or Alzheimer's diseases, which increase the cytoplasmic congestion, indeed have extremely unstable sleep-wake cycles. This proposes a new target for unstable sleep-wake cycles and cytoplasmic traffic jams.

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MS136

Deep Hybrid Modeling of Circadian Neuronal Excitability Using Generative Adversarial Networks

Mechanistic modeling and machine learning methods are powerful techniques for approximating biological systems and making accurate predictions from data. However, when used in isolation these approaches suffer from distinct shortcomings: model and parameter uncertainty limit mechanistic modeling, whereas machine learning methods disregard the underlying biophysical mechanisms. To address these shortcomings, we build Deep Hybrid Models (DeepHMs) that combine deep learning with mechanistic modeling to identify the distributions of mechanistic modeling parameters coherent to the data. One type of DeepHM uses Generative Adversarial Networks (GANs) to provide the inverse mapping from data to mechanistic model parameters. We employed GANs in a DeepHM to identify the mechanisms underlying day/night changes in the excitability of circadian clock neurons.

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MS136

Synchronization of Oscillators in the Presence of Competing Signals

The mammalian circadian clock is comprised of thousands of neurons, each of which has a weak circadian oscillation. Oscillations are coordinated via intercellular signaling, including neuropeptides. The network topology is complex, as there are multiple neuropeptides expressed by different neurons. Here, we consider a model of a heterogeneous clock with a complex network of potentially competing signals.

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MS137

Mechanistic Neural Masses Reveal Why Epileptic Brains Dont Seize All the Time

Epileptic brains experience instabilities to seizures and spreading depolarization (SD). It is not surprising that when a brain subnetwork receives large inputs it can be driven into one of these states through mechanisms by which first inhibitory network components are forced into depolarization block leading to runaway excitation, which propagates as seizures. A more subtle question is why epileptic networks aren't seizing all the time, and likewise why certain genetic mutations and therefore cellular-level functional changes, create networks that are inherently unstable. We have recently introduced Mechanistic Neural Masses (mNM - Tripathi and Gluckman, doi.org/10.3389/fnetp.2022.911090), which replace the sigmoidal firing rate functions commonly used in neural mass models of networks. mNMs are derived from Hodgkin-Huxley type membrane-level neural models, and parametrize firing rate and dynamical bifurcations as function of input and additional parameters such as extracellular potassium (K_o). Small networks of such mNMs reveal sensitivity of the network to seizure and SD is highly dependent on K_o, and that shifting excitatory/inhibitory balance can make such network more sensitive to K_o fluctuations. Additionally, this method allows us to propagate the empirical effects of epilepsy-associated genetic mutations through celluar models to understand their impact on network activity.

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MS137

Oral Glucose Tolerance Test Estimation and Dynamics from Electronic Health Record Data

Type 2 diabetes mellitus affects millions of patients, most for the rest of their lives once they contract the disease. Treatment is complex and costly, and complications from the disease occur despite treatment. Optimizing treatment requires knowing more about individual patients. Using mechanistic models of the glucose-insulin system, data assimilation, and data from electronic health records, we can estimate important physiologic patient characteristics that cannot be measured directly, like insulin sensitivity and use that to select treatment. We used oral glucose tolerance tests from health records to infer glucose-insulin state and infer outcomes after treatment.

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MS137

Modeling and Understanding Disease Progression with Deep Generative Models

Deep generative models are powerful tools for modeling data blending the representational power of neural networks with the flexibility of Bayesian networks. In this talk, Ill highlight two recent works on how theyve been used to predict and understand clinical data. Modeling the time-series of longitudinal data is important for predicting patient disease progression. Existing neural network-based approaches that learn representations of patient state, while flexible, are susceptible to overfitting. Ill describe a deep generative model that makes use of an attention based neural architecture inspired by the physics of how treatments affect disease state. The result is a scalable and accurate model of high-dimensional patient biomarkers as they vary over time. Unsupervised learning is often used to uncover clusters in data. However, different kinds of noise may impede the discovery of useful patterns from real-world data. Ill describe SubLign , a deep generative, continuous-time model of time-series data that clusters time-series while correcting for censorship time. Ill highlight provide under which clusters and the amount of delayed entry may be identified from data under a noiseless model. On real-world clinical datasets of heart failure and Parkinsons disease patients, Ill showcase how interval censoring can adversely affect the task of disease phenotyping and how SubLign corrects for these sources of error and recovers known clinical subtypes.

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MS137

Clocks in the Clinic: Circadian Rhythms in Health and Disease

Kidney function is regulated by the circadian clock. Not only do glomerular filtration rate (GFR) and urinary excretion oscillate during the day, the expressions of several renal transporter proteins also exhibit circadian rhythms. Interestingly, the circadian regulation of these transporters appears to be sexually dimorphic. Thus, the goal of this study is to investigate the mechanisms by which kidney function of the mouse is modulated by sex and time-of-day. To accomplish this, we have developed the first computational models of epithelial water and solute transport along the mouse nephrons that represent the effects of sex and circadian clock on renal hemodynamics and transporter activity. We conduct simulations to study how the circadian control of renal transport genes affects overall kidney function, and how that process differs between male and female mice. Simulation results predict that tubular transport differs substantially among segments, with relative variations in water and Na+ reabsorption along the proximal tubules and thick ascending limb tracking that of GFR. In contrast, relative variations in distal segment transport are much larger, with Na+ reabsorption almost doubling during the active phase. Model simulations of diuretics (a class of anti-hypertensive medications) predict different types of diuretics (loop, thiazide, or potassium-sparing diuretics) may have different efficacy depending on the time of administration.

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MS138

Universal Dynamics of Invasion Fronts

Front propagation into unstable states plays an important role in organizing structure formation in many spatially extended systems. When a trivial background state is pointwise unstable, localized perturbations typically grow and spread with a selected speed, leaving behind a selected state in their wake. A fundamental question of great interest is to predict the propagation speed and the state selected in the wake. The marginal stability conjecture postulates that speeds can be universally predicted via a marginal spectral stability criterion. In this talk, we will present background on the marginal stability conjecture and present some ideas of our recent conceptual proof of the conjecture in a model-independent framework focusing on systems of parabolic equations.

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MS138

Understanding Stochastic Waves in Cell Movement Models, from Modelling to (S)PDEs

Single-cell organisms are remarkably good at sensing food, especially if you consider that they lack our sensing organs and have to measure a gradient in the food supply over the length of a single cell. The precise mechanisms behind this gradient sensing are not fully understood yet. Still, scientists have determined many molecules that are relevant to the motion of the cell and we can see how these molecules are activated in wavelike patterns. These processes can be used to build Gillespie-type stochastic models for cell movement. These models are complex, both numerically and analytically, so we often summarise everything into 'simpler' PDEs. In this talk, I would like to advocate an in-between option, so-called Chemical Langevin Equations, effectively an SPDE approximation of the Gillespie algorithms. This approach allows us to use all the insights from the underlying deterministic PDE, without throwing away the stochastic nature of the models.

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MS138

Effect of Repelling Chemotaxis on Speed of Traveling Waves

This talk concerns an equation of Fisher-KPP type with a Keller-Segel chemotaxis term. We provide an almost complete picture of the asymptotic dependence of the traveling wave speed on parameters representing the strength and length-scale of chemotaxis. Our study is based on the convergence to the porous medium Fisher-KPP traveling wave and a hyperbolic Fisher-KPP-Keller-Segel traveling wave in certain asymptotic regimes. The talk is based on joint work with C. Henderson and Q. Griette.

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MS138

Stability of Pulled Pattern-Forming Fronts

Pattern formation is often nucleated when a localized disturbance grows and spreads, generating a pattern in the wake of this spreading. The marginal stability conjecture postulates that only those invasion speeds and patterns are selected for which the corresponding invasion front, connecting the ground state to this pattern, is marginally spectrally stable. Recently, the marginal stability conjecture was proven for the selection of spatially constant patterns by adapting sharp local stability results of the associated invasion front. In anticipation of extending the marginal stability conjecture to the selection of spatially inhomogeneous patterns, we established a sharp stability theory for pattern-forming invasion fronts. In this talk I focus on the case of pulled pattern-forming fronts, where marginal spectral stability manifests itself by two curves of essential spectrum touching the origin: one originating from the invaded ground state and the other from the periodic pattern in the wake. Such pulled pattern-forming fronts arise in the FitzHugh-Nagumo system, which was originally proposed as a simplification of the Hodgkin-Huxley model for nerve propagation and has since then attracted much interest as a phenomenological model for pattern formation. I will present a sharp nonlinear stability result for these fronts against suitably localized perturbations. This is joint work with Montie Avery (Boston University), Paul Carter (University of California, Irvine) and Arnd Scheel (University of Minnesota, Minneapolis).

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MS139

Stablizing Multilayer Geophysical Models Using the Hamiltonian Principle

Baroclinic instability is an important mechanism that facilitates the energy exchange between layers of large-scale geophysical flows. In a numerical model that is underresolved in the horizontal and/or vertical directions, the baroclinic instability is often suppressed, leading to a buildup of potential energy associated with the tilted layer interfaces that can not be released. In this work, we demonstrate, within the multilayer shallow water model and the Hamiltonian framework, how the baroclinic instability can be parameterized by adding an artificial potential energy term that is based on the slope of the interior layer interfaces. Numerical experiments will be carried out to assess the effectiveness of this approach.

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MS140

Stationary Distributions of Reaction Networks and the Chemical Recurrence Conjecture

Stochastic reaction networks are continuous-time Markov chain models typically used in biology, epidemiology, and population dynamics. What makes them special from a mathematical point of view is the fact that their qualitative dynamics is described by the finite directed graph of allowed reactions, referred to as "reaction graph". A longstanding conjecture is that models with a reaction graph composed by a union of strongly connected components are necessarily positive recurrent. In my talk I will discuss why the conjecture makes intuitive sense and why it is difficult to prove it. I will then show how my collaborators and I adapted Forster-Lyapunov techniques to prove the conjecture in two dimensions.

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MS140

Stochastic Reaction Networks Within Interacting Compartments

Stochastic reaction networks, which are typically modeled as continuous-time Markov chains on $\mathbb{Z}^d_{\geq 0}$, have proven to be a useful tool for the understanding of processes, chemical and otherwise, in homogeneous environments. There are multiple avenues for generalizing away from the assumption that the environment is homogeneous, with the proper modeling choice dependent upon the context of the problem being considered. One such generalization, introduced by Duso and Zechner in 2020, involves a varying number of interacting compartments, or cells, each of which contains an evolving copy of the stochastic reaction system. The novelty of the model is that these compartments also interact via the merging of two compartments (including their contents), the splitting of one compartment into two, and the appearance and destruction of compartments. We will discuss results pertaining to explosivity, transience, recurrence, and positive recurrence of the model, and explore a number of examples demonstrating some possible non-intuitive behaviors. Based on join work with David F. Anderson

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MS140

Combinatorics of Path Integrals for Stochastic Chemical Reaction Networks

Generating functions are used in combinatorics as a way of converting the enumeration of structures into a problem of computing the coefficients of a power series. In the theory of stochastic chemical reaction networks, probability generating functions similarly cast the probabilistic evolution of the system into a single partial differential equation encapsulating the whole dynamics. It might seem as though the generating functions used in combinatorics and probability theory are unrelated, but we will see that this is not the case. We will illustrate the equivalence of the dynamics of an arbitrary stochastic chemical reaction network and a class of directed bipartito graphs corresponding to reaction trajectories by means of their generating functions. We use the combinatorial representation to derive a decomposition of the dynamics in terms of trajectories corresponding to connected graphs.

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MS140

Refining Deterministic Approximations Of Stochastic Reaction Networks Through Dynamic Boundary Projection

To exactly compute the mean dynamics of stochastic reaction networks (SRNs), the solution of the Chemical Master Equation (CME) is rarely feasible. Often it is necessary to resort to computationally expensive simulations. To reduce the computational costs of this problem, several approximations have been proposed. The most common one is obtained considering a smaller set of ODEs, known as deterministic rate equations (DREs), that gives a macroscopic deterministic approximation of the average population dynamics. Unfortunately, it is known that DREs can be inaccurate for systems exhibiting significant intrinsic noise, unstable or multi-stable dynamics. Dynamic Boundary Projection (DBP) is a recently proposed method that couples together a truncated version of the CME, describing the evolution of a subset of states, and a set of DREs, used to shift the observed subset across the state space. It has been shown that it can be successfully applied to SRNs to refine the estimations of their mean dynamics even in the presence of oscillatory orbits, multi-scale populations, or multiple stable equilibria. In addition, to further reduce its computational costs, DBP can be coupled with suitable scaling techniques, that allow reducing the size of the observed state-space while preserving asymptotic properties.

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MS141

Transition Phenomena in Non-Gaussian Stochastic Dynamical Systems

Dynamical systems under non-Gaussian Levy fluctuations manifest as nonlocality at a certain macroscopic level. Transition phenomena are special events for evolution from one metastable state to another, caused by the interaction between nonlinearity and uncertainty. Examples for such events are phase transition, pattern change, gene transcription, climate change, abrupt shifts, extreme transition, and other rare events. The most probable transition pathways are the maximal likely trajectory (in the sense of optimizing a probability or an action functional) between metastable states. The speaker will present recent work (theory and methods) on the most probable transition pathways for stochastic dynamical systems, in the context of the Onsager-Machlup action functionals.

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MS141

Critical Scales for Noise-Driven Tipping in Nearly Non-Smooth Stommel-Type Models

We overview stochastic methods for studying dynamic bifurcations, relevant in canonical climate-related models and other applications. Our focus is on dominant factors in different scenarios of tipping, that is, where the transition related to the dynamic bifurcation may be advanced or delayed. Previous work has contrasted non-smooth and smooth dynamic bifurcations in the deterministic setting, indicating how noise and nearly non-smooth behavior can play a larger role in more realistic tipping models. The presence of high and low frequency forcing must also be considered, resulting in a competition between different important contributions, including stochastic forcing, high and low frequency components, the non-smoothness of the underlying bifurcations, bi-stability, and the slow variability of critical physical and environmental process. The analysis points to some fundamental differences in the smooth and non-smooth cases, which lead to a wider variety of tipping mechanisms in non-smooth-like settings.

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MS141

Noisy Tipping in Nonautonomous Systems

Rate-induced tipping occurs when a time-dependent ramp parameter changes rapidly enough to cause the system to tip between co-existing, attracting states. We demonstrate a prototypical example of rate-induced tipping influenced by stochastic forcing. We show that the addition of stochastic forcing to the system can cause it to tip well below the critical rate at which rate-induced tipping would occur. Moreover, it does so with significantly increased probability over the noise acting alone. We achieve this by finding a global minimizer in a canonical problem of the Freidlin-Wentzell action functional of large deviation theory that represents the most probable path for tipping. This is realized as a heteroclinic connection for the Euler-Lagrange system associated with the Freidlin-Wentzell action and we find it exists for all rates less than or equal to the critical rate. Its role as most probable path is corroborated by direct Monte Carlo simulations.

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MS142

Bifurcations of Periodic Solutions in a Vibro-Impact System with Dry Friction

Vibro-impact systems are nonlinear systems that can be employed in many engineering applications, such as energy harvesting. One such system consists of an inclined cylindrical capsule that is externally forced and a ball that is allowed to freely move inside the capsule. The ends of the capsule are covered with membranes made of dielectric elastomer material. Impacts between the ball and the membranes may lead to a net increase of electrical energy that may in turn be harvested. In this talk, combined numerical and analytical techniques, including nonlinear maps, capture bifurcation sequences representing periodic motions of different combinations of impacts at the top and bottom membranes. They are influenced by the addition of dry friction between the ball and the capsule. Dry friction results in sliding and sticking motions that may shift or alter the location of bifurcations as important parameters (e.g. the amplitude of the force or the length of the capsule) are varied. We contrast these results with previous studies in the absence of friction, revealing an interplay between smooth and non-smooth bifurcations, such as grazing.

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MS142

Reduction to Smooth Maps for the Global Dynamics of a Vibro-Impact Pair Model

Vibro-impact dynamic pairs appear in multiple engineering applications including vibro-impact harvesters. Such devices can harvester energy from vibro-impact motion of a ball moving freely within a driven cylindrical capsule with two dielectric elastomer membranes that cover its both ends. When the membranes are impacted and deformed by the ball, the capacitance change generates an extra charge to be harvested. Due to the complexity of the non-smooth interactions, there is a lack of mathematical approaches to analyzing the global dynamics of such vibro-impact systems. In this talk, we will present a computational method for reducing the non-smooth dynamics into smooth maps which represent the evolution of the systems states from one impact to another. These maps allow for a semi-analytical study of the systems global dynamics via an auxiliary 1D map approach for estimating the solutions basins of attraction. Our results may provide practical guidelines for designing vibro-impact energy harvesters with a desired globally stable dynamical regime that can maximize the energy gain.

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MS142

Adaptive Time-Stepping Methods Capturing Discontinuous and Stochastic Transitions in Non-Smooth Dynamical Systems

The analysis of discontinuous dynamical systems necessitates handling sudden changes in the underlying vector fields in the state space. Thus, it is important to ensure for numerical simulations that the adaptive time-stepping scheme does not miss the discontinuity boundary, otherwise the obtained trajectory would not render the appropriate depiction of the system's dynamics. The existing schemes broadly fall under two categories: the *event-tracking* schemes (for smaller number of events) and *event-capturing schemes* (for large number of events in higher dimensional configurations) [Acary, V. (2013), Computer Methods in Applied Mechanics and Engineering, 256, 224-250.]. This situation could get further complex when the system is subjected to irregular fluctuations [Kumar, P., *et. al* (2022), Nonlinear Dynamics, 1-24.]. This work deals with the development of appropriate adaptive time-stepping methods to precisely determine the discontinuity point at the surface of the switch. Additionally, the simulation of correct Brownian paths to apply variable time-integration schemes to a suite of non-smooth SDEs is addressed. The recursive generation of these irregular increments for reduced time steps for the case of correlated noises is also discussed. These methods could lead to accurate prediction of subtle phenomena like narrowband chaos, interior crises and intermittent noise-induced transitions in multi-stable stochastic non-smooth dynamical systems.

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MS142

Efficient Path Integration for the Computation of Response Probability Density Functions of Oscillators with Impacts

Several phenomena in engineering, biology, physics, and other sciences are modelled by dynamical systems with impacts and random excitation. One of the most important statistics escribing the response of dynamical systems to random effects is the probability density function (PDF). This PDF is also useful in the case of systems with impacts: we can not only analyse important properties of the dynamical system, such as n-th order moments and reliability but other derived statistics as well, such as the impact velocity distribution. In this talk, we extend the novel step matrix-multiplication based formulation of the path integration (SMM-PI) method to track the PDF of the time evolution of paths of vibro-impact oscillators. The SMM-PI method is based on the law of total probability captured by the Chapman-Kolmogorov (CK) equation, namely, we transform the CK equation to a matrix-vector multiplication utilising high-order numerical time stepping and interpolation methods. To demonstrate the efficiency and the high convergence rate of the method, we use the resulting step matrix to obtain the time-dependent and steady-state PDFs of a linear oscillator with a single and with a pair of impact barriers. Then we apply the SMM-PI method to analyse the energy output of a vibro-impact energy harvester, represented by a vibroimpact oscillator, which generates energy at each impact using dielectric elastomers.

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MS143

Momentum Stiefel Optimizer, with Applications to Orthogonal Attention, and Optimal Transport

I will report the construction of momentum-accelerated algorithms that optimize functions defined on Riemannian manifolds, focusing on a particular case known as Stiefel manifold. That means optimizing functions of matrices with orthonormal columns that are not necessarily square. The treatment will be based on the design of continuous- and discrete-time dynamics. Two practical applications will also be described: (1) we markedly improved the performance of trained-from-scratch Vision Transformer by appropriately wiring orthogonality into its self-attention mechanism, and (2) our optimizer also makes the useful notion of Projection Robust Wasserstein Distance for high-dim. optimal transport even more effective.

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MS143

Implicit Bias of Large Learning Rate

Recent empirical advances show that training deep models with large learning rate often improves generalization performance. However, due to challenges in analysis, theoretical justifications on the benefits of large learning rate are highly limited under non-convex problems like neural network models, even for basic algorithms like gradient descent (GD). In this talk, it will be shown that large learning rates provably bias toward flatter minimizers, which arguably generalizes better. More precisely, even if the algorithm is initialized near a sharp minimizer, with large enough learning rates, it can still converge to a flatter minimum instead of the closer ones. The region of large learning rates will also be demonstrated through a simplified neural network model, where the convergence theory of GD is valid for constant learning rates well beyond 2/L, where L is the largest eigenvalue of Hessian at the initialization.

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MS144

Modeling the Migrations of the Capelin: Ecological Response to Climate Change

Some chemical reactions catalyzed by enzymes show enhanced diffusion, where the diffusivity of the enzyme through the substrate is unexpectedly high. Based on the 2018 work of Canalejo et al., we developed an agent-based model on a lattice to simulate such reactions. Using the model, we are able to examine the patterns produced by the simulations and compare the diffusion rates against those experimentally observed. We also derive a system of PDEs which exhibits cross-diffusion and is similar to that in the aforementioned paper by Canalejo et al.

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MS144

Modeling Alignment in Swarming: Local vs. Non-Local Models

Biological aggregations (fish schools, insect swarms) are governed by social interactions, notably alignment with conspecifics. For agent-based models of alignment we consider two strategies for deriving PDEs governing the population density. The first (which is non-local in space) assumes the populations are locally aligned. The second models orientation at each point in space as a distribution. We show how these strategies can be used to model foraging hopper bands of the Australian plague locust for which we have access to field data. Numerical simulations and dynamical systems methods allow insight into advantages and drawbacks of these strategies for reproducing biological-observed behaviors.

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MS144

Consensus and Separation Dynamics of a Swarm-Sphere Model with Attractive and Singular Repulsive Kernels

In this talk, we present an agent-based interacting particle system with attractive and singular repulsive forces on the sphere. We show that singular repulsive kernels induce collision avoidance among particles from different groups. We also provide a sufficient condition for the emergence of asymptotic consensus in the same group and separation for different groups. Moreover, we consider the one-dimensional case, i.e. particles on the circle, separately due to their different dynamics from multidimensional cases.

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MS144

Living Orbs of Light: The Physics of Firefly Communication

Fireflies offer a unique and rare glimpse into animal communication. Their signal comprises a species-specific on/off light pattern repeated periodically, used by individual fireflies to advertise themselves to potential mates. Detecting individuals becomes increasingly challenging at high densities of fireflies. In this talk, I will explore how fireflies approach this problem while using physics and information-theory concepts, e.g., energetic cost and compression (minimization of bits representing information) and detectability (high signal-to-noise-ratio). The first approach involves signal amplification via synchronization within swarms containing tens of thousands of individuals. Our recent quantitative measurements of the three-dimensional spatiotemporal flashing pattern of synchronous firefly swarms allow us to validate a set of mathematical models that account for short-range spatial correlations and the signal's emergent periodicity. The second approach involves the evolutionary design of light patterns with increased detectability at other individuals' expense. Using a computational model, we observe an emergent periodicity in the resulting optimal sequences and demonstrate a method of reconstructing potential cost functions from the phylogenetic relationships of extant species alongside their characteristic flash patterns.

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MS145

Recent Results of Rigorous Numerical Integration for Higher Spatial Dimensional PDEs

In this talk we introduce a rigorous integrator for numerically verifying solutions of time evolutionary partial differential equations (PDEs) near a neighborhood of numerically computed approximate solutions. A fixed-point formulation using a solution operator (called the evolution operator) of the linearized problem at the approximate solution yields a hypothesis for proving the existence of the solution locally in time. By numerically validating this hypothesis, rigorous integrator is successfully achieved for including the exact solution. This method can be applied to a general class of time evolutionary equations. In particular, we focus on the application to higher spatial dimensional PDEs. We believe that our rigorous integrator contribute computer-assisted proofs for PDEs.

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MS145

Periodic Traveling Waves in the Suspension Bridge Equation

The one-dimensional suspension bridge equation has been well studied: traveling waves of various types have been proven to exist. Far less is known about the two-dimensional case. We use computer-assisted proof methods to find and prove many periodic traveling waves in two spatial dimensions.

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MS147

Analysis of Point-Contact Models of the Bounce of

a Golf Ball Against a Compliant Frictional Surface

Inspired by the turf-ball interaction in golf, this talk discusses the bounce of a ball that can be modelled as a rigid sphere and the surface as supplying an elasto-plastic contact force in addition to Coulomb friction. A general formulation is presented that models the finite time interval of bounce from touch-down to lift-off. Key to the analysis is understanding transitions between slip and roll during the bounce. Starting from the rigid-body limit with a an energetic or Poisson coefficient of restitution, it is shown that slip reversal during the contact phase cannot be captured in this case, which result generalises to the case of pure normal compliance. Yet, the introduction of linear tangential stiffness and damping, does enable slip reversal. This result is extended to general weakly nonlinear normal and tangential compliance. An analysis using Filippov theory of piecewise-smooth systems leads to an argument in a natural limit that lift-off while rolling is non-generic and that almost all trajectories that lift off, do so under slip conditions. Moreover, there is a codimension-one surface in the space of incoming velocity and spin which divides balls that lift off with backspin from those that lift off with topspin. The results are compared with recent experimental measurements on golf ball bounce and the theory is shown to capture the main features of the data.

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MS147

Application of Piecewise-Smooth Periodic Orbit Bifurcation Analysis on Machining Contact Loss, Linear Guide Stick-Slip, and Traffic Dynamics Problems with Time Delays

A periodic orbit continuation framework is introduced for general nonlinear piecewise-smooth delay differential equations, based on spectral collocation techniques. Formulating the infinite dimensional multi-point boundary value problem of periodic orbits in an adaptively discretized manner allows numeric evaluation of periodic orbits, continuation of such solutions in system parameters, identification and continuation of piecewise-smooth system specific bifurcations, and furthermore, direct evaluation of stability employing the Implicit Function Theorem. The proposed framework is presented through three practical engineering applications. First a boring operation in the presence of a displacement constrained tuned mass damper is investigated, where due to rigid body impacts bistable zones appear on the stability charts, with boundaries that can be identified through continuation of grazing periodic orbits. Then a flexible moving column of a machine tool subject to Stribeck-type friction and position control delay is investigated via the derivation of quasi-frequency response functions through the continuation of piecewise-smooth periodic orbits, while through the continuation of sliding bifurcations stick-slip parameter domains are also identified. Finally, a low degree of freedom ring model of highway traffic is investigated containing both human and AI controlled vehicles, both with multiple mode controllers, that alternate between cruise control and accident prevention.

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MS147

Parametric Study of Targeted Energy Transfer Through Vibro-Impact System Using Map Based Approach

Targeted energy transfer (TET) is a passive mechanism for the mitigation of excess vibration of a linear oscillator (LO) by means of unidirectional energy transfer to the secondary system. For effective TET over broadband frequency range, a nonlinear energy sink (NES) is attached to the LO. Traditionally, this is achieved by attaching a secondary mass with cubic stiffness and a linear damper to the LO. Recent studies explore vibro-impact (VI) systems, where a ball oscillates inside the LO, for TET in which energy is getting transferred through the impacts and results in controlled vibration of the LO. However, the existing literature explores VI-NES for TET when the frequency ratio is close to one and the mass ratio is also very small. This study investigates the effect of different parameters of VI-NES on TET over a broad range for different periodic solutions. The numerical results are verified with the analytical results obtained through the map-based approach which are derived for different periodic solutions.

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MS147

Limit Cycle Oscillations from n-dimensional Boundary Equilibria Bifurcations

Impacting hybrid systems are non-smooth systems, characterized by continuous flow and a discrete reset map dynamics. In the planar case, all bifurcation cases are known. But there is no such general theory in higher-dimensional system, and there is no known dimension reduction method like centre manifold theory in discontinuous system to simplify the problem. Our study is motivated by two applied problems involved boundary-equilibrium bifurcations; namely models for an aeroelastic win-flap model, and a pressure relief valve. We focus on the possibility of birth limit cycle oscillations. We derive a semi-analytical method to detect the existence and stability of period-one oscillations around the boundary equilibrium bifurcation in a general n-dimensional impacting hybrid system. Some well-known results are reproduced in the 2D case, and we illustrate the more general possibilities in 3D cases, as well as explaining the observed dynamics in the two applied examples. Meanwhile, we show how our smooth explicit condition can be combined with numerical continuation to perform parametric analysis. Possible extensions are discussed to boundary equilibrium bifurcations in switching systems comprised of two continuous flows.

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MS148

A Dynamical Perspective on Optimization Methods for Machine Learning

We will discuss recent connections between optimization methods and continuous-time dynamical systems. In particular, several known methods in the optimization literature can be seen as discretizations of the same dynamical system, and accelerated variants of these methods as discretizations of a simple classical Hamiltonian system. From this perspective, optimization methods can also be constructed by exploring symplectic integrators (in a dissipative setting), in unconstrained and constrained settings. Other types of mechanical systems, e.g., exploring a relativistic dynamics, also lead to new optimization methods. We will mention how rates of convergence of these dynamical systems translate to discretizations by exploring a backward error analysis approach.

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MS148

Using Coupling Method to Detect Underlying Dynamics, with Applications to Machine Learning

In this talk I will present our recent result about using numerical coupling method to detect properties of dynamical systems. I will first discuss how to use numerical coupling technique to estimate the speed of convergence of a stochastic differential equation towards its steady state. Then I will show how to connect the property of deterministic dynamics and coupling time distributions by running the coupled process with different magnitudes of noise. Applications to studying the loss surfaces of deep neural networks will be demonstrated.

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MS148

Optimization with Momentum and Constraints: A Perspective from Smooth and Non-Smooth Dynamics

My presentation will discuss a class of first-order methods for constrained optimization that are based on an analogy to non-smooth dynamical systems. The key underlying idea is to express constraints in terms of velocities instead of positions, which has the algorithmic consequence that optimizations over feasible sets at each iteration are replaced with optimizations over local, sparse convex approximations. The result is a simplified suite of algorithms and an expanded range of possible applications in machine learning.

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MS148

Convergence in KL Divergence of the Inexact Langevin Algorithm with Application to Score-based Generative Models

We study the Inexact Langevin Algorithm (ILA) for sampling using estimated score function when the target distribution satisfies log-Sobolev inequality (LSI), motivated by Score-based Generative Modeling (SGM). We prove a long-term convergence in Kullback-Leibler (KL) divergence under a sufficient assumption that the error of the score estimator has a bounded Moment Generating Function (MGF). Our assumption is weaker than L^∞ (which is too strong to hold in practice) and stronger than L^2 error assumption, which we show not sufficient to guarantee convergence in general. Under the L^∞ error assumption, we additionally prove convergence in Rényi divergence, which is stronger than KL divergence. We then study how to get a provably accurate score estimator which satisfies bounded MGF assumption for LSI target distributions, by using an estimator based on kernel density estimation. Together with the convergence results, we yield the first end-to-end convergence guarantee for ILA in the population level. Last, we generalize our convergence analysis to SGM and derive a complexity guarantee in KL divergence for data satisfying LSI under MGF-accurate score estimator.

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MS149

Dynamical Systems and Control-Theoretic Properties of Overparametrized Linear Regression

Recent research in neural networks and machine learning suggests that using many more parameters than the initial complexity of a regression problem can result in more accurate or faster-converging models – contrary to classical statistical belief. This phenomenon, sometimes known as benign overfitting', raises questions about in what other ways might overparameterization affect the properties of a learning problem. In this work, we investigate the effects of overfitting on the robustness of gradient-descent training when subject to uncertainty on the gradient estimation. This uncertainty arises naturally if the gradient is estimated from noisy data or directly measured. Our object of study is a linear neural network with a single, arbitrarily wide, hidden layer and an arbitrary number of inputs and outputs. We notice that the overparametrized formulation introduces a set of spurious equilibria which did not exist before and lay outside the set where the loss function is minimized. We proceed to characterize the input-to-state stability property with respect to inputs (disturbances in gradient) for several different scenarios. We then study the behavior of the general case when around an arbitrary equilibrium point. The set of initial conditions that does not converge to our target set has a much smaller dimension than our parameter space for the undisturbed case, but the presence of disturbances adds a nonempty region of attraction to our spurious equilibria.

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MS149

An Algorithm for Bayesian Filtering in Uniformly Hyperbolic Dynamics

In a Bayesian filtering problem, the goal is to sample from a sequence of filtering distributions, which are probability distributions of the state of a dynamical system conditioned on past observations. Of interest here is the setting where the dynamical system is chaotic. Filtering algorithms based on measure transport – transformation of samples from a reference to a typically complex target measure – are increasingly receiving attention since they are broadly applicable, e.g., in non-Gaussian settings and due to recent computationally scalable techniques for parameterizations of such transformations, called transport maps. However, such techniques, including stochastic map filters and neural network-parameterizations, do not yet exploit the structure in the target (filtering) distributions that arises from the underlying chaotic dynamics. Here we propose an ansatz for the transport map in uniformly hyperbolic systems. We develop a non-parametric method to compute it by using i) classical methods for conjugacies in dynamics and ii) a novel score-matching algorithm. We demonstrate this iterative algorithm for measure transport-based filtering on uniformly hyperbolic systems with one-dimensional unstable manifolds.

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MS149

Analyzing Parameter Identifiability Using a Dimension Reduction Approach to Model Calibration for Applications in Mathematical Oncology

The inference of model parameters for moderate- to high-dimensional differential equations can be challenging, as the full set of parameters is often unidentifiable in the sense that they are not uniquely determined by the available data. Additionally, the computational cost of performing Bayesian inference in a high-dimensional space may not allow for adequate exploration of the entire parameter domain. These issues may be mitigated by using active subspace techniques to identify the subspace of identifiable inputs, then exploiting this subspace to explore only those directions in the input space that will actively inform parameter estimates. In this talk, we explore multiple methods for using the active subspace to assist with model calibration and demonstrate their use on a tumor growth model for which the original parameter set is unidentifiable.

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MS149

Combining Machine Learning and Dynamical Systems to Model Cancer Growth

Traditional mathematical modeling approaches to investigating biological questions, such as ordinary or partial differential equations, are interpretable and are able to predict future states. However developing dynamical systems models require constant refinement and are laborious to develop. On the other hand, machine learning approaches are quick, but may lack interpretability and the ability to predict into the future. Here we combine mathematical modeling approaches with machine learning methods to obtain accurate, interpretable models directly from spatiotemporal data, bypassing the need for model refinement. We test the hybrid methodology with examples from biological applications in cancer. We use synthetic data that mimics many of the difficulties we face with biological data such as high proportional errors and few time points.

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MS150

The Opportunities and Challenges of Solving Differential Equations in Quantum Computing

In this talk, we will compare the mesh-based and mesh-free method of solving differential equations in quantum computing. For the mesh-free method, we will focus on the method using multilayer quantum neural network with single qubit. We will prove that using a variational algorithm, we can approximate any bounded complex function and use it to create a differential equation solver algorithm.

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MS150

Synchronization of Heterogeneous Forced Kuramoto Oscillator Networks: A Differential Inequality Approach

A differential inequality approach is utilized to derive several stability conditions for synchronizing heterogeneous first-order forced coupled Kuramoto oscillator networks. In this talk, we shall show that if either the amplitude of the external force is large enough or all natural frequencies equal to the external frequency, the heterogeneous first-order forced coupled Kuramoto oscillator network will reach the frequency synchronization for any initial condition. In particular, when all natural frequencies equal to the external frequency, a phase synchronization can be achieved when the amplitude of external force is not zero and the initial configuration is confined to a half circle. For non-identical cases, we show that if the average of all natural frequencies equals to the external frequency, the coupling strength is relatively large compared to the differences of natural frequencies and the amplitudes of external forces, and the initial configuration is confined to a half circle, the heterogeneous first-order forced coupled Kuramoto oscillator network still exhibit a frequency synchronization.

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MS150

Pattern-Selective Feedback Stabilization of GinzburgLandau Spiral Waves

The complex GinzburgLandau equation serves as a paradigm of pattern formation and the existence and stability properties of GinzburgLandau m-armed spiral waves have been investigated extensively. However, many multi-armed spiral waves are unstable and thereby rarely visible in experiments and numerical simulations. In this talk we explain how to selectively stabilize certain significant classes of unstable spiral waves within circular and spherical geometries. As a result, stable spiral waves with an arbitrary number of arms are obtained for the first time. Our tool for stabilization is the symmetry-breaking control triple method, which is an equivariant generalization of the widely applied Pyragas control to the setting of PDEs.

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MS150

Approximating Delay Equations by Finite Dimensional Systems: Pseudospectral Approximation and Computer-Assisted Proofs

In pseudospectral approximation for DDE, one uses a discretization procedure to approximate a delay differential equation (DDE) by an ordinary differential equation (ODE). It promises to be a useful approach to numerically approximate dynamical properties of DDE, such as bifurcation behaviour and invariant manifolds. In this talk, we use methods from rigorous numerics and computer assisted proofs to analyze how unstable manifold are approximated in the pseudospectral method. Given a DDE and an approximating ODE with fixed discretization index, we outline the procedure to compute the error between the unstable manifold of the ODE and the unstable manifold of the DDE. This is joint work with Shane Kepley.

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MS151

Data Assimilation for the 2D Rotating NSE on the β plane

With sufficiently fast rotation, the solution of the periodic 2D rotating NSE on the β plane becomes nearly zonal. Furthermore, the bounds on the number of degrees of freedom (determining modes/nodes) reduce with faster rotation and are fewer than in the case of non-rotating 2D NSE. We validate this analytically and numerically in the context of continuous data assimilation via nudging.

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MS151

Toward Faster, More Realistic Data Assimilation: New Results and Analysis

A major difficulty in accurately simulating turbulent flows is the problem of determining the initial state of the flow. For example, weather prediction models typically require the present state of the weather as input. However, the state of the weather is only measured at certain points, such as at the locations of weather stations or weather satellites. Data assimilation eliminates the need for complete knowledge of the initial state. It incorporates incoming data into the equations, driving the simulation to the correct solution. The objective of this talk is to discuss innovative computational and mathematical methods to test, improve, and extend a promising new class of algorithms for data assimilation in turbulent flows and related systems. We will look at classical and modern approaches, and then examine, via live simulations, a few new ideas which are a little different, but which in many cases give better results with fewer resources.

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MS151

A General Involution Framework for Metropolis-Hastings Algorithms and Applications to Bayesian Inverse Problems

We consider a general framework for Metropolis-Hastings algorithms used to sample from a given target distribution on a general state space. Our framework has at its core an involution structure, and is shown to encompass several popular algorithms as special cases, both in the finite- and infinite-dimensional settings. In particular, it includes random walk, preconditioned Crank-Nicolson (pCN), schemes based on a suitable Langevin dynamics such as the Metropolis Adjusted Langevin algorithm (MALA), and also ones based on Hamiltonian dynamics including several variants of the Hamiltonian Monte Carlo (HMC) algorithm. In addition, our framework comprises algorithms that generate multiple proposals at each iteration, which allow for greater efficiency through the use of modern parallel computing resources. Aside from encompassing existing algorithms, we also derive new schemes from this framework, including some multiproposal versions of the pCN algorithm. To illustrate effectiveness of these sampling procedures, we present applications in the context of certain Bayesian inverse problems in fluid dynamics. In particular, we consider the problem of recovering an incompressible background fluid flow from sparse and noisy measurements of the concentration of a passive solute advected by the flow.

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MS151

Concurrent Multi-Parameter Learning for Dissipative PDEs

We introduce an algorithm based on the nudging data assimilation scheme for the concurrent (on-the-fly) estimation of scalar parameters for a system of evolutionary dissipative partial differential equations in which the state is partially observed. The algorithm takes advantage of the error that results from nudging a system with incorrect parameters with data from the true system. The intuitive nature of the algorithm makes its extension to several different systems immediate, and it allows for recovery of multiple parameters simultaneously. We test the method on the Kuramoto–Sivashinsky equation in one dimension and demonstrate its efficacy in this context.

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MS152

Critical Desynchronization of Power Grids

A particular complexity of the power grid stability is caused by the fact that the desired synchronous state is only locally stable, not globally stable. In such a case the desired grid synchrony can be secured only against small perturbations but not against large impacts, even applied to a single grid element or to a single connection. If so, the system's dynamics can switch to another, desynchronized attractor as soon as large perturbation is applied. The essential difficulties of the power grid studies are also induced by intricate, highly asymmetric architectures of realistic grids. What is the role of asymmetry for the stability? Which grids with symmetric or asymmetric topology are more reliable? We attack this problem by examining a symmetric power grid model and compare its stability with the situation when the symmetry is broken by elementary violations of the network structure.

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MS152

How Modular Structure Influences the Synchronization Stability of Power-Grid Nodes

A power grid is one of the world's largest networked systems that consists of power producers, power consumers, and transmission lines. Since it can be mapped into a network topology, network science has been used to investigate the power-grid dynamics such as cascading failure and synchronization stability. So far, the local (or nodal) network properties have provided numerous clues to understand the synchronization dynamics of a power grid. Now, we try to expand our understanding about the synchronization stability to the community. A community refers to a group of nodes in a network that are densely connected. The dense connection can enhance their interaction and naturally impacts the nodes' response to external perturbations. However, it is not trivial whether the clustered connection will exacerbate the disturbance,reducing stability, or promote recuperation, letting the system relax fast. We show that the node attributes related to consistent community membership have an impact on successful synchronization recovery. In particular, the more constant membership a node has, the more stable the node is. In addition, we also find that the effective function of a group of nodes as a communitya consumer or a producer groupdetermines the overall distribution of partial synchronization stability. We introduce the Chilean and German power grid as case studies to show how community influences the synchronization stability of power-grid nodes.

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MS152

Stability Concepts for Power Grids for Strong Perturbations

The human brain, power grids, climate, or arrays of coupled lasers are all characterized by multistability. The stability of each of the existing solution is typically studied via linear stability analysis, a linearization-based approach. However, this is in many real systems too local because there often rather large perturbations appear. Instead, we discuss sample-based approaches. One is basin stability, a measure related to the volume of the basin of attraction.

Another is related to desired regimes of complex systems, also called safe operational space leading to the notion of survivability: Given a random initial condition, what is the likelihood that the transient behaviour of a system does not leave a region of desirable states. Both measures can be rather easily calculated even for high dimensional systems. Their potentials will be demonstrated especially for modern power grids as well as climate and brain. It should be emphasized that the properties of measures based on survivability are not captured by common asymptotic stability measures as basin stability. The concept of basin stability can be also efficiently used for a bifurcation analysis of high-dimensional systems.

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MS152

Functional Observability and Target State Estimation in Large-Scale Networks

Observing the internal states of a network system via measurement and/or estimation is fundamental for the prediction, control, and stabilization of large-scale complex systems, such as power grids. High dimensionality, however, poses physical and costs constraints on sensor placement, limiting our ability to make a network observable. Noting that often only a relatively small number of state variables are essential for control, intervention, and monitoring purposes in large-scale networks, we propose a graph-based theory of functional observability [1]. A system is functionally observable when a targeted subset of state variables can be reconstructed from the available measurements, and our results establish conditions under which this is possible for network systems. Based on the developed theory, we further design two highly-scalable algorithms to: (i) place a minimal set of sensors to ensure the network functional observability and (ii) design the corresponding functional observer (estimator) with minimum computational cost. Our methods are applied to cyberattack detection in power grids, where functional observers are designed to detect false data injected in communication channels across the system. The applications demonstrate that our results can achieve accurate estimation with substantially fewer resources. [1] A. N. Montanari, C. Duan, L. A. Aguirre, A. E. Motter. PNAS, 119:e2113750119 (2022).

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MS153

Rigorous Computation of Solutions of Semi-Linear Partial Differential Equations on Unbounded Domains via Spectral Methods

In recent years, rigorous numerics have become a major tool to prove solutions of Partial Differential Equations (PDEs). However, when the equation is set on an unbounded domain of $\mathbb{R}^m$ (where $m > 1$), only a few results have been obtained so far. In this talk, I will present a general method to rigorously prove strong solutions to a large class of nonlinear PDEs in a Hilbert space $H^l \subset H^s(\mathbb{R}^m)$ ($s \geq 1$) via computer-assisted proofs. We first introduce a method to rigorously compute an upper bound for the norm of the inverse of the linearization of PDE operators. The method is purely spectral and the constants are determined through Fourier analysis. Then using a Newton-Kantorovich approach, we develop a numerical method to prove existence of strong solutions to PDEs. As an application, we prove a soliton in the Kawahara equation in $H^4(\mathbb{R})$ as well as a localized pattern in the 2D Swift-Hohenberg equation in $H^4(\mathbb{R}^2)$.

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MS153

Computer Assisted Proof of drift orbits in some chaotic systems

We will discuss a method for proving the existence of diffusion orbits based on results by Gidea, De La Llave and Seara for systems with Normally Hyperbolic Invariant Manifolds along the homoclinic connections. The mechanism relies on the outer dynamics exclusively. The inner dynamics, and its invariant objects (primary, and secondary tori, lower dimensional hyperbolic tori and their stable/unstable manifolds etc) are not used at all. We present topological and functional analytical methods for computing rigorous enclosures of the invariant manifolds. Diffusion is established on a large interval of the action variable using high order approximations of the manifolds.

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MS153

A posteriori analysis of a pseudospectral method for solving delay differential equations

A powerful method for approximating solutions of scalar delay differential equations is to discretize and then interpolate the solution. We present a framework for making quantitative and rigorous estimates of the error in this approximation and validating these estimates via computer assisted proof.

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MS153

A Trefoil Knot in the Lorenz Equations

Numerical evidence, going back to the 1986 work of Glendinning and Sparrow, suggests the existence of invariant trefoil knots in the Lorenz systems. These knots are formed by intersections of the one dimensional manifolds of the Lorenz system's three equilibrium solutions, and the ends of the knot pass through infinity. Since the phenomenon requires the intersection of one dimensional manifolds in a three dimensional phase space, such a knot cannot be generic. Rather, it requires moving two of the systems three parameters. These matters (and other important global bifurcations) are described in great detail in the 2015 paper of Creaser, Krauskopf, and Osinga. I will discuss a computer assisted existence proof of a heteroclinic trefoil knot in the Lorenz system, at the classic parameter values considered in the references above. The proof is formulated in a functional analytic style, so that the parameters of the system appear explicitly in the equations. The functional equation for the heteroclinic orbit is solved numerically by projecting onto a polynomial (Taylor series) basis. A true solution is obtained from the numerical approximation using a Newton-Kantorovich type a-posteriori argument. The method is general and should, in principle, be sufficient for proving the existence of other kinds of global bifurcations. This is joint work with Sheldon Newhouse.

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MS154

Projection Schemes and Uncertainty Quantification in Spatially-Extended Neurobiological Networks

Neural field models are nonlinear integro-differential equations for the evolution of neuronal activity, and they are a prototypical large-scale, coarse-grained neuronal model in continuum cortices. Neural fields are often simulated heuristically and, in spite of their popularity in mathematical neuroscience, their numerical analysis is not yet fully established. We introduce generic projection methods for neural fields, and derive a-priori error bounds for these schemes. We extend an existing framework for stationary integral equations to the time-dependent case, which is relevant for neuroscience applications. We find that the convergence rate of a projection scheme for a neural field is determined to a great extent by the convergence rate of the projection operator. This abstract analysis, which unifies the treatment of collocation and Galerkin schemes, is carried out in operator form, without resorting to quadrature rules for the integral term, which are introduced only at a later stage, and whose choice is enslaved by the choice of the projector. We give examples of concrete projection methods: two collocation schemes (piecewise-linear and spectral collocation) and two Galerkin schemes (finite elements and spectral Galerkin); for each of them we derive error bounds from the general theory, introduce several discrete variants, provide implementation details, and present reproducible convergence tests.

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MS154

When Curvature Promotes or Obstructs the Ability of a Pacemaking Region to Drive Activity in Excitable Tissue

In cardiac tissue, the sinoatrial node (SAN) is responsible for initiating the periodic electrical pulses underlying heart beats. However, other regions of local heterogeneous tissue (e.g., ischemic regions) can act as rogue pacemakers and produce oscillations in neighboring tissue that compete with the natural pacemaking of the SAN and cause potentially life-threatening arrhythmias. Thus, it is important to understand the physiological conditions that enable the SAN to robustly act as the cardiac pacemaker and for local depolarized regions of tissue to form pathological rhythms. It is well known that small heterogeneities (sources) should not be able to easily activate a large area of excitable tissue (sink). On a local level, this source-sink balance implies that positive curvature of a pacemaking region reduces the ability to drive the neighboring tissue. However, while numerous studies provide evidence that supports the source-sink balance relationship in which high curvature deters oscillations, other studies have shown that for some depolarized heterogeneities, oscillations tend to emerge from corners and other areas of high curvature. Here, we use an idealized two-domain reaction-diffusion system and corresponding two-cell model to bridge the gap between these seemingly opposing viewpoints. In doing so, we identify the conditions for which curvature of a pacemaking region promotes or obstructs the production of oscillations in the neighboring tissue.

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MS154

Understanding and Treating Arrhythmias Using Biophysical Models of the Heart

Digital twins of the heart are increasingly used to understand disease mechanisms, predict outcomes and personalise therapies. They are creating by solving the differential equations that describe cardiac physiology, using information from medical imaging, electrical signals and other measurements as inputs. I will show digital twins can lead to improved understanding of atrial fibrillation and can help personalise treatments for this condition. I will also show how neural networks, especially physics-informed neural networks, can contribute to the creation and deployment of cardiac digital twins.

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MS154

Fronts, 'Surfing' Peaks, and Global Bifurcations in a Multi-Variable Morphogenetic Model of Branching

We study the existence and stability of fronts (heteroclinic connections in space) in Meinhardt's reaction-diffusion model of branching in one spatial dimension. We identify a saddle-node-infinite-period (SNIPER) bifurcation of fronts that leads to episodic front propagation in the parameter region below propagation failure and show that this state is stable. The organization of uniformly traveling fronts is studied using numerical continuation, revealing additionally, several unexpected properties of front connections related to a series of distinct global T-point bifurcations, which are also responsible for a large multiplicity of different bound fronts-peak solutions. On the other hand, below the SNIPER bifurcation, the fronts show a distinct behavior which we refer to as 'surfing' peaks owing to the resemblance to jumping oscillons. The results indicate that multivariable models may support new types of behavior that are absent from typical two-variable models but may nevertheless be important in developmental processes such as branching and somitogenesis.

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MS155

Epilepsy Surgery: Evaluating Robustness Using Dynamic Network Models

Epilepsy is a neurological disorder that affects over 65 million people worldwide. Nearly a third of epilepsy patients do not respond to medication (refractory) and can potentially benefit from brain surgery. Unfortunately, the complexity in identifying the brain regions responsible for seizure generation and spread represent a great challenge and only a small proportion of refractory patients are considered for surgical treatment. Additionally, surgical outcomes are often non-optimal and seizures tend to return over time. Many computational methods that combine mathematical modelling, network analysis, and brain imaging data have recently been developed to predict the impact of surgical resection and support surgical planning. Most of these methods, however, tend to consider that representations of the brain network do not change after surgery, ignoring brain plasticity and how brain network reorganization could influence seizure susceptibility long after the surgery. We will discuss the importance of post-surgical network reconfiguration in seizure propensity. We will describe how dynamic network models can be used to simulate seizure transition in representations of brain networks, to estimate seizure propensity both before and after in silico resections. We will also demonstrate how network reconfiguration after the virtual surgery can lead to an increase in seizure propensity and propose a framework to estimate robustness to surgical strategies.

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MS155

Modelling Seizure Triggers As Perturbations to An Epileptic Landscape

Epilepsy is a chronic and complex neurological disorder affecting about 65 million people globally. It manifests as pathological electrical activity in the brain and may lead to recurrent, unprovoked seizures, affecting the quality of life. The perceived unpredictability of seizures remains the primary concern of people with epilepsy. However, several studies have shown that external and physiological triggers such as stress, anxiety and sleep deprivation may play a precipitating role in initiating seizures. We propose a mathematical framework that quantifies the compounding effect of seizure triggers in leading up to a seizure. We propose that the state of an epileptic brain could be characterized in terms of an epileptic landscape, wherein a globally stable spiral sink exists during the interictal state (the period outside seizures). The seizure triggers are modelled as parameter perturbations that slowly warp this epileptic landscape over time, giving rise to an ictal (seizure-like) state, which are modelled as stable limit cycles. We elucidate that, two bifurcation parameters are needed to characterize this transition from the interictal to the ictal state. We present new equations that describe the dynamics of these bifurcation parameters in terms of the seizure triggers. The equations help to assess how close we are to the bifurcation and to scout for interventions that could reverse the effect of these triggers and prevent the bifurcation that activates seizures.

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MS155

Optimization of Ictal Aborting Stimulation Using the Dynamotype Taxonomy

Electrical stimulation is an increasingly popular method to terminate epileptic seizures; yet it is not always successful. A potential reason for inconsistent efficacy is that stimuli are applied empirically, without considering the underlying dynamical properties of a given seizure. We use a computational model of seizure dynamics to show that different seizure types from the Taxonomy of Seizure Dynamics have disparate responses to aborting stimulation. In the model, the aborting input is realized as an applied stimulus forcing the system from a bursting state to a quiescent state. This transition requires bistability, which is not present in all classes. We examine how topological and geometric differences in the bistable state affect the probability of termination as the seizure progresses from onset to offset. We find that the most significant determining factors are the presence or absence of a DC shift and the seizures dynamotype (onset/offset bifurcations). We find that seizures that have a DC shift are far more likely to be terminated due to the necessary structure of state space in which these seizures occur. Furthermore, we observe that the probability of termination varies throughout the seizures duration and is correlated to dynamotype. Our model provides a method to predict the optimal method of termination for each dynamotype. We conclude that strategies for aborting seizures with ictal stimulation must account for seizure dynamotype to optimize efficacy.

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MS155

A Realistic High-Resolution Brain Model of Epilepsy

Epilepsy is a serious neurological disease, causing recurrent unprovoked seizures, which is affecting around 50 million people worldwide. Current treatment options are medication, surgical removal of the epileptic tissue and stimulation. Computational modelling and dynamical systems theory can help to further our understanding about seizure dynamics and possible intervention strategies. In this work we build a patient specific high resolution virtual brain model of a patient with temporal lobe epilepsy. Cortical geometry and white matter connectivity are reconstructed from MR imaging to build the structural scaffold of the model. The 2D Epileptor model establishes a spatially continuous excitable neural field and allows simulating seizure like dynamics on the cortex. We identify regimes of traveling waves and re-entry excitations in the parameter space corresponding to sustained seizure activity. Targeted lesioning of connectivity and electric stimulation are proposed as possible intervention strategies to prevent re-entry excitations and stop seizures.

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MS156

Ticking and Talking in the Brainstem Satiety Centre: A Phase Model of Three Clocks

Analysis of the Per2 bioluminescent rhythm previously recorded in the ex vivo mouse dorsal vagal complex (DVC) reveals a characteristic phase relationship between three distinct circadian oscillators: the area postrema (AP), the nucleus of the solitary tract (NTS), and the ependymal cells surrounding the 4th ventricle (4Vep). The data suggests a consistent phasing, where the AP peaks first, followed immediately by the NTS, with the 4Vep in near-antiphase. Wavelet analysis shows that this pattern is not consistently maintained throughout the recording, however, the phase dynamics strongly imply the presence of oscillator interactions. In this talk, I will present a simple phase model that simulates realistic phase dynamics between the three oscillators when the coupling is close to a synchronization transition. The coupling topology suggests that the AP bidirectionally communicates phase information to NTS and 4Vep to synchronize the three structures. Comparing the model with previous experimental manipulations demonstrates its feasibility to explain DVC circadian phasing. Finally, we show that simulating steadily decaying coupling improves the model's ability to capture experimental phase dynamics.

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MS156

It's All About Time!

Light and temperature constitute two major entrainers of the circadian timing systems. Understanding how photic signals are transduced through the SCN and how core body temperature exerts its influence on peripheral cells is critical for understanding the emergence of biological rhythms in the peripheral tissues. In this work, we discuss semi-mechanistic mathematical models that capture the essential hierarchical structure of the photic and temperature signal transduction through the SCN, leading to rhythmic patterns of endocrine hormones (cortisol) and peripheral clock genes. We analyze the implications of disrupted light signals, in the form of jetlag and shift work, as well as the implications of alterations in core body temperature rhythms. Such model predictions would add insights toward the understanding of the organization of the central timing system and the health implications of disrupting, and restoring circadian rhythms.

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MS156

A Mean-Field Firing-Rate Model for the Suprachiasmatic Nucleus

We present a mean-field formalism for modeling firing-rate statistics of brain regions whose neurons exhibit atypical firing patterns and heterogeneous electrophysiological properties. We apply the formalism to the suprachiasmatic nucleus (SCN)the human circadian pacemaker-whose neurons can intrinsically exhibit depolarized low-amplitude membrane oscillations (DLAMOs), depolarization block (DB), and standard action potential firing at different times of day. Further, reversal potentials and molecular circadian phases of SCN neurons, among other properties, vary across the network and/or slowly over time. Our formalism consists of a system of integro-differential equations describing the time evolution of the mean and standard deviation of synaptic conductances across the network. Electrophysiological properties of SCN neurons are incorporated by computing responses to synaptic conductance inputs of a Hodgkin-Huxley-type SCN neuron model that exhibits DLAMOs and DB. Such responses are then averaged over distributions of relevant quantities and included in the differential equations. Results suggest mechanisms by which physiologically relevant changes to firing activities may arise. For instance, results show that a large spread in circadian phases across SCN neurons reduces the size of oscillations in SCN network firing activity across the 24h day, thereby influencing circadian rhythms.

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MS156

A Kuramoto Model Reveals How Heterogeneous Food Entrainable Oscillators Mediate Food Anticipatory Activity

Many species have robust daily activity rhythms that can be driven by the timing of food intake. In particular, rats exhibit food anticipatory activity that is conceptualized to be the output of food entrainable oscillators. The cellular or molecular foundation of these oscillators have yet to be determined. Nonetheless, many interesting phenomena related to food anticipatory activity have been observed. Our experiments show that rats with running wheels can anticipate at least four daily feeding opportunities at fixed times of day and that anticipation persists at each mealtime during several circadian cycles of food deprivation in constant dark. These anticipatory behaviors also occur in rats with an ablated suprachiasmatic nucleus, the site of the central circadian pacemaker. We also observe rats anticipating two daily meals recurring with 24h and 26h periodicities that also persists during constant darkness food deprivation. We capture all of these dynamic phenomena with a mathematical model. This model consists of two groups of Kuramoto oscillators, representing the suprachiasmatic nucleus and the food entrainable oscillators. The two populations are intra- and inter-coupled and receive adapted photic input. We hypothesize that the period heterogeneity of the food entrainable oscillators is primarily responsible for the food anticipatory activity. We analyze this model using numerical simulations and the Ott-Antonson ansatz in a continuum limit. The model provides a framework to analyze previous experiments and design future experiments.

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MS157

New Insights into Binocular Rivalry from the Reconstruction of Evolving Percepts Using Model Network Dynamics

When the two eyes are presented with highly distinct stimuli, the resulting percept generally switches every few seconds between the two monocular images in an irregular fashion, giving rise to a phenomenon known as binocular rivalry. While a host of studies have explored potential mechanisms for binocular rivalry in the context of model dynamics in response to simple stimuli, here we investigate rivalry directly through complex stimulus reconstructions based on the activity of a two-layer network model with competing downstream pools driven by disparate image stimuli. To estimate the dynamic percept, we derive a linear input-output mapping rooted in the nonlinear network dynamics and iteratively apply compressive sensing techniques for signal recovery. Utilizing a dominance metric, we identify when percept alternations occur and use data collected during each dominance period to generate a sequence of percept reconstructions. We show that the dominant monocular image is well encoded in the network dynamics and improvements are garnered when realistic spatial receptive field structure is incorporated. Our model demonstrates gamma-distributed dominance durations and well obeys Levelt's four laws, agreeing with key experimental observations. In light of evidence that individuals with autism exhibit weakened binocular rivalry, we corroborate the hypothesis that autism manifests from reduced inhibition by probing our model alternation rate across choices of inhibition strength.

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MS157

Quantitative Relations Among Causality Measures with Applications to Nonlinear Network Reconstruction

The causal connectivity of a network is often inferred to understand the network function. However, the interpretation of causal connectivity remains unclear, particularly regarding how it depends on causality measures and relates to structural connectivity. We focus on nonlinear networks with pulse signals as measured output (e.g., neural networks with spike output) and address these issues based on four commonly used causality measures: time-delayed correlation coefficient, time-delayed mutual information, Granger causality, and transfer entropy. We theoretically demonstrate how these measures are related to each other quantitatively when applied to pulse signals. Taking the simulated Hodgkin-Huxley neural network and the real mouse brain network as two illustrative examples, we further show that the causal connectivity inferred by any of the four measures coincides with the underlying structural connectivity, creating a direct link between causal and structural connectivity. Our pairwise reconstruction framework of structural connectivity can be achieved without conditioning on global information from all other nodes in a network, providing an effective approach for pulse-output network reconstruction.

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MS157

Aging of Neurons Reconciles Flexibility and Stability of Memory: Dual Structural Plasticity in the Olfactory System

The capacity to learn and store memories is one of the most important functions of the brain, but these two abilities are inherently at odds with each other: a network of neurons must be flexible enough to quickly store new information, but it must be stable enough to prevent old memories from being overwritten. Metaplasticity in which the timescale of synaptic modifications made by an individual neuron changes could resolve this flexibility-stability trade-off. We propose that this strategy may be implemented by the mammalian olfactory bulb (OB), where newborn, highly plastic neurons are being added throughout adulthood that become less plastic as they age. Here, we present a biophysically inspired computational model of the OB to investigate synaptic integration of adult-born neurons and their impact on learning and memory. In line with experiments, we show how memories are encoded by young adult-born neurons, how these memories are briefly vulnerable to interference from a new stimulus, how re-learning a lost memory is faster than learning a new memory, and how the OB can learn several odors at the same time. Finally we use the model to make predictions including how odor exposure leads to birthdate-dependent, odor-specific subnetworks forming in the OB.

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MS158

Stability of a Wave Front Connecting Two Unstable States

The properties of wave fronts often comes down to the stability of their asymptotic states. Bistable fronts, that connect two constant stable equilibria, are subject to exponential stability up to a phase. Monostable fronts, sometimes called invasion fronts, that connect a stable to an unstable equilibria are shown to be asymptotically stable in weighted spaces, without phase shift. In this presentation, we will discuss the properties of a wave front connecting two unstable states, and in particular its asymptotic stability properties.

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MS158

Modulating Fronts in Pattern-Forming Systems with Oscillatory Instability

Consider a pattern-forming system, where a homogeneous ground state destabilizes via an oscillatory instability as a parameter increases beyond a critical value. That is, at the critical value, there is a critical mode at Fourier wave numbers $\pm k_c^*$, which has zero real part, but non-vanishing imaginary part. This is also called a Turing-Hopf bifurcation and can for example be observed in the Taylor-Couette problem and a flow down an inclined plane. In this scenario, one expects that a periodic wave train with non-zero phase velocity bifurcates from the homogeneous ground state. Moreover, close to the onset of instability, the wave trains typically arise in the wake of an invading heteroclinic front, which connects the unstable ground state to the periodic wave train. In this talk, I will consider this instability in a one-dimensional dispersive Swift-Hohenberg equation coupled to an additional dispersive conservation law. Here, the dispersive terms break the reflection symmetry $x \mapsto -x$ and lead to a Turing-Hopf bifurcation. I will present an existence result for so-called *modulating traveling fronts*, which model the invasion of the homogeneous ground state by the bifurcating periodic wave train. I will also present a classification of the obtained modulating fronts in terms of their spreading speed in relation to the phase and group velocity of the bifurcating wave train.

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MS158

Transverse Pattern Formation in the Cahn-Hilliard Equation in the Wake of a Quench

The Cahn-Hilliard equation is used to model phase separative pattern formation in many contexts, such as binary alloy mixtures, chemical precipitation, and evaporative deposition experiments, and can form many different types of patterns. In two spatial dimensions, we study which types of transversely modulated patterns can be selected in the wake of a simple plateau quenching heterogeneity. Such a heterogeneity spatially progressively travels across the domain with fixed speed, exciting patterns in its wake. We show that two families of patterns, induced by $O(2)$-symmetry in the system, generically arise via a Hopf bifurcation from the background front as the quenching speed is varied.

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MS159

Point-Vortex Solutions for 2D Flow

Point vortex models play an important role in the study of two-dimensional incompressible fluid dynamics. They have been originally derived by Helmholtz, about 130 years ago, but many interesting questions are still open. In this talk, we discuss a certain class of point vortex models, namely generalized surface quasigeostrophic models. We state some of it basic properties, derive a inhomogeneous mean field - thermodynamical limit, from the discrete Hamiltonian system, by using a variational principle. We discuss fluctuations around the limit law and the usage and interpretation of these models in statistical physics. This is joint work with Marco Romito (Uni Pisa) and funded by the Crafoord foundation.

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MS159

Pathwise Solutions for the Stochastic Hydrostatic Euler Equations

The hydrostatic Euler equations, also known as the inviscid primitive equations, are utilized to describe the motion of inviscid fluid flow in a thin domain, such as the ocean and atmosphere on a planetary scale. In this talk, I will present some recent progress on the stochastic version of this model. Specifically, I will demonstrate how the local Rayleigh condition can be used to address the issue of ill-posedness, leading to the establishment of the existence and uniqueness of pathwise solutions.

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MS159

Spontaneous Suppression of the Inverse Energy Cascade by the Generation of Shielded Vortices in Instability-Driven Two-Dimensional Turbulence

Instabilities of fluid flows often generate turbulence. Using extensive direct numerical simulations, we study 2D turbulence driven by a scale-localized instability superposed on stochastic forcing, in contrast to earlier studies of state-independent forcing. We vary a parameter γ which controls the fraction of energy injected by the instability. As γ increases, the system undergoes two transitions. Below a first threshold $\gamma < \gamma_1$, a regular large-scale vortex condensate forms. For $\gamma \geq \gamma_1$, shielded vortices (SVs) emerge and coexist with the condensate. At a second, larger value γ_2, the condensate collapses, and a gas of weakly interacting vortices with broken symmetry spontaneously emerges, characterized by a preponderance of vortices of one sign only and suppressed inverse energy cascade. The number of SVs in this broken symmetry state slowly increases via a random nucleation process. At late times, a dense SV gas emerges, persisting down to small γ, where it forms a hexagonal lattice. Individual SVs are trapped in the lattice at small γ, up to a sharp threshold γ_0, above which the mean square displacement of SVs increases with time, i.e. the lattice melts. Multistability occurs between dense SV states (intact/molten lattice), the condensate and mixed condensate-SV states, over a wide range of γ. Our findings provide new evidence for a strong dependence of 2D turbulence phenomenology on the forcing.

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MS160

Wave Propagation and Bifurcation in Diffusive Systems: a Perspective Motivated by Neuroscience

The talk will focus on the wave-propagation phenomenon in a Neuroscience context. I will start with qualitative results arising in a Non-Homogeneous Reaction-Diffusion System of FitzHugh-Nagumo (FHN) type and then discuss connections with other models relevant in Neuroscience: from chain of kicked FHN to forced Laplace equations, from bumps arising in network models of calcium activation in the drosophila to synchronization in networks of periodically forced Hodgkin-Huxley PDE. This talk is intended to give a global picture of the mini-symposium and to highlight important problematics involved.

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MS160

Mechanisms for Recovery in Integrate-and-Fire Networks Impacted by Axonal Swelling

Focal axonal swelling is a result of traumatic brain injury, wherein the axons of individual neurons in the cerebral cortex experience in variation in width along their length. The impact of such an injury has been probed in simulations at the single-neuron level by modeling the axon as a cable of varying width. These simulations have shown that focal axonal swelling can have a nonlinear deleterious effect in propagation of spike-encoded signals. Due to the significant computational cost of solving the cable equation, we have developed an efficient algorithm that faithfully reproduces the cable model's behavior in propagating spike train stimuli. Our work leverages this algorithm to assess the impact of focal axonal swelling at the network level, specifically considering the frequency processing abilities of layered feedforward networks of integrate-and-fire neurons. In addition, we consider the impact that modifications to these networks may have on their robustness to such damage. We find that in our tested networks, the addition of presynaptic inhibitory neurons always increases or leaves unchanged the network's robustness to damage. This indicates a potential mechanism for how networks of neurons may adapt to maintain cognitive function despite the presence of damage in the occurrence of a traumatic brain injury.

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MS160

Complex Cascades of Depolarization Arising from Periodic Stimulation of FitzHugh-Nagumo Chains

Periodic stimulation of an excitable FitzHugh-Nagumo neuron (FHN) leads to a complicated response due to the rich dynamics supported by timescale separation. While a strong regular sequence of current injections at low frequency induces a correspondingly regular sequence of depolarizations, a weaker injection at higher frequency may lead to "skipped beats corresponding to the dynamics missing the excitability threshold. The ensuing patterns of skipped vs. present beats in the response can be surprisingly rich and correspond to a distinctive intracellular mechanism for mixed-mode oscillations (MMOs) in the neurons membrane potential. We report here some basic results in an idealized setting, where a feedforward chain of identical FHN cells is presented a periodic stimulus in the form of Dirac kicks at its front node, and the resulting signal propagation is assessed downstream. In particular, we find that the front end of the chain acts as an effective signal filtration system that results in a regular lower frequency depolarization at sufficiently downstream sites. Of note, and a problem of current investigation, the front-end block corresponding to chain filtration can be arbitrarily long, and the MMO dynamics within the cells involved there can be complex and different at each site. Overall, our results give mathematical insight into certain aspects of electrical signal propagation through neural tissues, an area of active current interest and research in neuroscience.

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MS161

A Data-Driven Approach for Discovering the Most Probable Transition Pathway for a Stochastic Carbon Cycle System

Many natural systems exhibit tipping points where changing environmental conditions spark a sudden shift to a new and sometimes quite different state. Global climate change is often associated with the stability of marine carbon stocks. We consider a stochastic carbonate system of the upper ocean to capture such transition phenomena. Based on the Onsager-Machlup action functional theory, we calculate the most probable transition pathway between the metastable and oscillatory states via a neural shooting method. Furthermore, we explore the effects of external random carbon input rates on the most probable transition pathway, which provides a basis to recognize naturally occurring tipping points. Particularly, we investigate the transition pathway's dependence on the transition time and further compute the optimal transition time using a physics-informed neural network, towards the maximum carbonate concentration state in the oscillatory regimes. This work may offer some insights into the effects of noise-affected carbon input rates on transition phenomena in stochastic models.

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MS161

An End-to-End Deep Learning Approach for Extracting Stochastic Dynamical Systems Witha-Stable Lvy Noise

Recently, extracting data-driven governing laws of dynamical systems through deep learning frameworks has gained much attention in various fields. Moreover, a growing amount of research work tends to transfer deterministic dynamical systems to stochastic dynamical systems, especially those driven by non-Gaussian multiplicative noise. However, many log-likelihood based algorithms that work well for Gaussian cases cannot be directly extended to non-Gaussian scenarios, which could have high errors and low convergence issues. In this work, we overcome some of these challenges and identify stochastic dynamical systems driven by a-stable Lvy noise from only random pairwise data. Our innovations include (1) designing a deep learning approach to learn both drift and diffusion coefficients for Lvy induced noise with a across all values, (2) learning complex multiplicative noise without restrictions on small noise intensity, and (3) proposing an end-to-end complete framework for stochastic system identification under a general input data assumption, that is, an a-stable random variable. Finally, numerical experiments and comparisons with the non-local KramersMoyal formulas with the moment generating function confirm the effectiveness of our method.

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MS161

Learning Effective Dynamics from Data-Driven Stochastic Systems

Multiscale stochastic dynamical systems have been widely adopted to a variety of scientific and engineering problems due to their capability of depicting complex phenomena in many real world applications. This work is devoted to investigating the effective dynamics for slow-fast stochastic dynamical systems. Given observation data on a short-term period satisfying some unknown slow-fast stochastic systems, we propose a novel algorithm including a neural network called Auto-SDE to learn invariant slow manifold. Our approach captures the evolutionary nature of a series of time-dependent autoencoder neural networks with the loss constructed from a discretized stochastic differential equation. Our algorithm is also validated to be accurate, stable and effective through numerical experiments under various evaluation metrics.

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MS161

Three-Dimensional Numerical Study on Wrinkling of Vesicles in Elongation Flow Based on the Immersed Boundary Method

We study the wrinkling dynamics of three-dimensional vesicles in a time-dependent elongation flow by utilizing an immersed boundary method. For a quasi-spherical vesicle, our numerical results well match the predictions of perturbation analysis, where similar exponential relationships between wrinkles' characteristic wavelength and the flow strength are observed. Using the same parameters as in the experiments by Kantsler et al. [Phys. Rev. Lett. 99, 178102 (2007)], our simulations of an elongated vesicle are in good agreement with their results. Besides, we get rich three-dimensional morphological details, which are favorable to comprehend the two-dimensional snapshots. This morphological information helps identify wrinkle patterns. We analyze the morphological evolution of wrinkles using spherical harmonics. We find discrepancies in elongated vesicle dynamics between simulations and perturbation analysis, highlighting the importance of the nonlinear effects. Finally, we investigate the unevenly distributed local surface tension, which largely determines the position of wrinkles excited on the vesicle membrane.

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MS162

Experimental Bifurcation Analysis of Neurons Using Control-Based Continuation

Control-based continuation (CBC) and phase-locked loop (PLL) testing are experimental methods for identifying dynamical features of physical systems. We start by providing a general introduction to these methods, then survey recent work on applying CBC to biological systems, with an emphasis on studying cellular excitability dynamics. The dynamics of excitable cells such as neurons are well-understood – biological communities have developed a sophisticated arsenal of experimental methods and associated theory to study and explain observed behaviours, and the mathematical community has complemented this with a bifurcation-theoretic framework and associated suite of numerical and analytical tools. In this talk, we highlight some novel results on combining the numerical perspective of mathematicians and the experimental techniques of biologists. Using CBC, numerical continuation and bifurcation analysis methods are performed directly on a living cell, within a dynamic clamp experiment. The bifurcation diagram is generated entirely from cellular dynamics, without any model or modelling assumptions. Benefits of the dynamic clamp will be highlighted, mathematical aspects of the algorithm will be discussed, and the practicalities of applying numerical continuation to biological systems will be considered.

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MS162

Model-Free Continuation Using Discrete and Continuous-Time Adaptive Control

Control-based continuation embeds a physical experiment in a feedback control loop with control input parameterized by an experimentally accessible reference signal and designed such that the response to zero control input is that of the original system. Provided the closed-loop behavior of interest exhibits asymptotic convergence to limit cycle dynamics uniquely determined by the reference input, the feedback design is non-invasive if a reference input exists for which the control input converges to zero. As an alternative to linear, non-adaptive feedback control strategies, which may require significant gain tuning and provide no a priori guarantees of bounded performance, we consider the integration of nonlinear adaptive control strategies with principles of control-based continuation for tracking fixed points of uncertain discrete-time systems and periodic orbits of uncertain continuous-time dynamical systems. In contrast to the linear, non-adaptive case, we find problem-dependent limitations on the type of adaptive control strategies for which we can prove asymptotic convergence to steady-state dynamics that is locally independent of initial conditions and uniquely determined by the given reference input, even in instances where bounded performance can be guaranteed. For certain problem classes, we describe candidate adaptive control strategies that meet all the requirements of control-based continuation, while overcoming the limitations of non-adaptive controllers.

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MS162

Control-Based Continuation of Deformable Bubbles in Experiments

We study the propagation of deformable air bubbles driven through a fluid-filled channel with large aspect ratio, a system known to exhibit a rich range of dynamical behaviour in experiments. This system is classically modelled by depth-averaged equations, leading to predictions of an infinite sequence of steadily-propagating solutions, only one of which is linearly stable. However it is not clear to what extent these predicted unstable states persist into the real 3D system. Our overall aim in this work is to use control-based continuation (CBC) to detect and explore unstable states directly in our experiments. We develop a system of feedback control for the propagating bubble, with feedback delivered through time-dependent fluid injection at the sides of the channel, with amplitudes determined from real-time observation of the bubble shape. We use the model itself as an initial test bed to design a suitable control gain and overcome the complexities of controlling a propagating bubble moving past a fixed array of actuators. For CBC, the target state is unknown a priori, but detected so that the control amplitudes are zero at steady state (non-invasive control), leading to new bifurcation structures as the target state is varied. We explore the effect of noise and delay in this system, with particular reference to our experiments in progress for a deformable but stationary bubble.

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MS162

Experimental Characterisation of Mode Interactions Using Control-Based Continuation

Without the need for a mathematical model, control-based continuation (CBC) is a means to apply the principles of numerical continuation directly to a physical system and experimentally track particular types of responses as adjustable parameters are modified. However, reliably and efficiently tracking responses during tests is challenging. Most existing path-following methods are ideal only in a numerical context where the solution path is smooth, and derivatives can be evaluated to high precision. This is not easily achievable in experiments where solutions and derivative estimates are corrupted by measurement noise. In this talk, I investigate the use of an algorithm combining CBC and Gaussian process regression (GPR) to significantly improve the reliability of the continuation process. Experimental demonstration is performed by tracking frequency response, backbone and limit-point bifurcation curves on a cantilever beam with local nonlinearity and harmonically-coupled modes. The extension of the method to the identification of mode interactions is then discussed.

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MS163

One Shot Learning of Stochastic Differential Equations with with Data Adapted Kernels

We consider the problem of learning Stochastic Differential Equations of the form $dX_t = f(X_t)dt + \sigma(X_t)dW_t$ from one sample trajectory. This problem is more challenging than learning deterministic dynamical systems because one sample trajectory only provides indirect information on the unknown functions f, σ. We propose a method that combines Computational Graph Completion and data adapted kernels. Our approach can be decomposed as follows: (1) Represent the time-increment map $X_t \to X_{t+dt}$ as a Computational Graph in which f, σ and dW_t appear as unknown functions and random variables. (2) Complete the graph (approximate unknown functions and random variables) via Maximum a Posteriori Estimation (given the data) with Gaussian Process (GP) priors on the unknown functions. (3) Learn the covariance functions (kernels) of the GP priors from data with randomized cross-validation.

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MS163

Discovering Shared Causal Drivers from Nonlinear Time Series Measurements

Many experimental measurements arise from subsystems that implicitly share a common driving signal. In systems biology, examples include targets of transcription factors, regulation of circadian rhythms, and descending control in animal nervous systems. Previous theoretical work on attractor reconstruction suggests that partial information present in each subsystem can reveal subregimes within the unseen driving signal, introducing the possibility of fully recovering the driver given sufficient data. Here, we connect this problem to existing work on skew product dynamical systems, and we show that these results motivate a new type of manifold learning algorithm based on persistent homology. We show empirical results demonstrating the ability to reliably detect a common driving signal from complex time series, even in the presence of many noisy, incomplete measurements. We show applications to real-world datasets including species abundances in microbial ecosystems and simultaneous recordings of neurons.

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MS163

Kernel Methods for Forecasting Irregularly Sampled Time Series

A highly efficient way to predict the future of a dynamical system is to interpolate its vector field with a kernel, where the kernel parameters are learned with an algorithm called Kernel Flows (KF) , which uses gradient-based optimization to learn a kernel. KF is based on the premise that a kernel is good if there is no significant loss in accuracy when half of the data is used for interpolation. However, the KF algorithm fails if the observed time series is not regularly sampled in time. In our paper, we solve this problem with a generalization of the flow map of the dynamical system by incorporating time differences between observations in the KF data-adapted kernels. Upon comparison with the original KF algorithm, we found that our simple modification significantly improved the forecasting accuracy.

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MS164

Recent Advances in Weak Form Sparse Identification of Nonlinear Dynamics (WSINDy)

Data-driven modeling approaches have proven highly successful in a wide range of fields in science and engineering. In this talk, I will discuss several ubiquitous challenges with the conventional model development / discretization / parameter inference / model revision loop. I will present our Weak form Sparse Identification of Nonlinear Dynamics (WSINDy) framework which addresses several of these challenges and offers substantial advantages in terms of computational efficiency, noise robustness, and modest data needs (in an online learning context). Lastly, I will illustrate applications of WSINDy to several benchmark problems as well as some of our recent improvements to the algorithm.

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MS164

Model-Identification Techniques to Inform Dynamics of Regulatory Systems

Regulatory networks are the molecular systems through which organisms run developmental programs, process information, and make decisions. Ordinary differential equations derived from mass action kinetics are commonly used to describe dynamic regulatory systems. Interactions between regulatory elements such as promoters and inhibitors which increase and decrease genetic expression of proteins can be captured using rational functions. Identification of which of these terms best produces a specific dynamic response can be performed using techniques that rapidly search the space of possible interactions and find equations structure or rational function terms that most closely match the dynamic signals. These methods can be used to suggest likely mechanisms occurring in experiments or perform the design of genetic circuits which meet an operational goal. I will discuss our current progress in using sparse optimization and genetic search algorithms to identify gene regulatory systems for scientific understanding and engineering design.

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MS164

Identifying Transitions Between Collective Motion Regimes Using Statistical Significance Tests on Time-Varying Persistence Homology Data

We explore one of the open questions in the study of collective pattern behavior. In biological systems, the interactions of entities or self-propelled particles with their neighbors can lead to a ”coherent state”, meaning the formation of aggregation patterns due to the local alignment of speed and direction. This work describes a process that determines the transition time when a collection of interacting particles starts to behave coherently after starting from an incoherent, disordered state. We use persistent homology to capture the topology of the particle configuration at any particular time instance. Transition is localized in time using a bisection scheme consisting of repeating the statistical significance tests on appropriately chosen subsets of the time-varying persistent homology outputs. We demonstrate the robustness of our methodology to the choice of filtered simplicial complex, the choice of persistence landscape distance measure, and the variation in particle density. We validate our approach on a synthetic stochastic model representing self-propelled interacting particles, where the regime transition is triggered externally by changing the model parameters during the simulation. Next, we apply the technique to a collection of cervical cancer cell tracks obtained from in vitro experiments of cell migration.

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MS164

Machine Learning of Collective Behaviors from Observation

Collective Behaviors (aka Self Organization) occurs naturally in bird flocking, cell aggregation, ant raiding, locust swarm, etc. It is challenging and intriguing to understand self organization from the mathematical point of view. We offer a statistical/machine learning approach to explain collective behaviors from observation data; moreover, our learning approach can aid in validating and improving the modeling of collective behaviors. We develop a learning framework to derive physically meaningful and physical dynamical systems to explain collective behaviors from observation. We then investigate the steady state properties of our learned estimators. We also extend the learning approach for dynamical models constrained on Riemannian manifolds. We further improve our learning capability to infer interaction variables as well as interaction kernels. We even study the effectiveness of our learning method on the NASA Jet Propulsion Laboratory's modern Ephemerides. A complete learning theory on second-order systems is presented, as well as two new models on emergence of social hierarchy and concurrent emergence of flocking and synchronization.

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MS165

Disturbing the Big Bang

We will give an introductory talk on the dynamics of the Big Bang singularity and perturbations thereof. This topic has attracted a great deal of attention of both mathematicians and physicists since the heuristic approach of BelinskiKhalatnikovLifshitz (known as BKL conjecture/picture) and the Mixmaster attractor construction of Misner. We will see how a specific perturbation of the Big Bang singularity will unravel well-known and brand new dynamical features. Moreover, we will see how such perturbations yield good (or bad) approximating schemes of the usual Einstein's general theory of relativity. These results were fruit of collaborations with K.E. Church (U Montreal), V.H. Daniel (Columbia U), J. Hell (FU Berlin), O. Hnot (McGill U), J.P. Lessard (McGill U), H. Sprink (FU Berlin) and C. Uggla (Karlstad U).

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MS165

A Degenerate Logistic Equation

We will present some recent results on existence and behavior of solutions for a class of semilinear parabolic equations, defined on a bounded smooth domain, with a nonlinear term which is asymptotically linear at infinity, or else for degenerate logistic nonlinearities. Global solutions are obtained and their behavior is analysed when the initial data varies in the phase space. In particular, the so called Nehari manifold is used to separate the phase space into regions of initial data where uniform boundedness or grow-up behavior of the semiflow may occur. This is a work in collaboration with L. Maia.

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MS165

The Sgn of the Traveling Wave Speed in the Lotka-Volterra Competition Model

The sign of the traveling wave speed in the two species Lotka-Volterra Competition diffusion system with strong competition is very important issue. Due to the bi-stable condition, the traveling wave solutions dont have the minimum wave speed. So, the sign of wave speed becomes very important. In this talk, I will briefly introduce our problem first and give some examples. Next, I will show our technique min-max characterization and main result. The detail calculation and future works will be discussed if time is available.

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MS166

Going Mobile; If Pete Towns(h)end were to do Data Assimilation

We analyze a nudging data assimilation algorithm for the periodic 2D Navier-Stokes equations in which observations are confined to a window that moves across the entire domain along a predetermined path at a given speed. We prove that, if the movement is fast enough, then the algorithm synchronizes with a reference solution. The analysis suggests an informed scheme in which the subdomain moves according to the region where the error is dominant. Numerical simulations are presented which compare the efficacy of three types of movement: one that follows a regular pattern, one guided by the dominant error, and one that is random.

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MS166

Dimension Reduction for Data Assimilation: Particle Filters with Reduced Order Models and Data

Particle filters are a class of data assimilation techniques that can estimate the state and uncertainty of dynamical models by combining nonlinear evolution models with non-Gaussian uncertainty distributions. However, estimating high dimensional states, such as those associated with spatially discretized PDE models, requires an exponentially large number of ensemble members or particles to avoid the so-called filter collapse. This dramatically decreases the accuracy and efficiency in obtaining the estimation. By combining particle filters with projection-based data-driven model reduction techniques, such as Proper Orthogonal Decomposition and Dynamic Mode Decomposition, we demonstrate that it is possible to reduce the effective dimension of the models and reduce the occurrences of filter collapse for a class of dynamical models relevant to forecasting of geophysical fluid flows. This technique can be adapted to account for models with transient change in parameters, by developing time dependent projection matrices using window snapshots. We demonstrate several variants of the technique on Lorenz96-type models and on a simulation of shallow-water equations.

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MS167

Increasing the Resilience of Power Grids to Mitigate Future Extreme Weather Events

The Texan electrical network in the Gulf Coast of the United States is frequently hit by Tropical Cyclones (TC) causing widespread power outages, a risk that is expected to increase under global warming. Here, we introduce a new approach of combining a probabilistic line fragility model with a network model of the Texas grid to simulate the temporal evolution of wind-induced failures of transmission lines and the resulting cascading power outages from seven major historical hurricanes. The approach allows reproducing observed supply failures and identifying the most vulnerable sections of the grid. It shows that damages do not just accrue over time, but that the failure of specific critical lines can trigger large cascades. Hardening just a small number of these critical lines substantially increases the resilience of the grid to TC strikes. So protection of only 1% of lines can reduce the likelihood of the most destructive type of outages by a factor of between 5 and 30. The proposed modelling approach could represent a tool so far missing to efficiently strengthen the power grids against future hurricane risks even under limited knowledge.

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MS167

Complex Frequency Control of Grid Forming Inverters

Due to the energy transition power plants are replaced by renewable energy sources (RES). RES such as Wind turbines and solar cells are connected to the power grid via power-electronic-inverters. As we move towards a fully renewable grid, there is a growing need for so-called grid-forming inverters (GFIs) that can contribute to grid stability. This shift presents a significant challenge as GFIs are a relatively new and complex technology, of which there is a limited practical and theoretical understanding. Especially the stability of inverter-based networks remains a challenging topic. We provide a new formulation of the problem of GFIs based on the closely related concepts of the complex frequency introduced by Milano [1], and the so-called normal form of GFIs [2]. Using the normal form it is possible to eliminate the complex voltage from the equations, giving self-contained dynamics featuring only the power flows and voltage amplitudes. Remarkably we find an even simpler formulation of the power grid dynamics in terms of time-varying couplings in which even the dependence on the grid topology vanishes. This novel formulation is particularly promising to study the dynamic stability and control of inverter-based networks. [1] F. Milano, Complex Frequency, IEEE Transactions on Power Systems, 2022 [2] R. Kogler et al., Normal Form for Grid-Forming Power Grid Actors, PRX, 2022

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MS168

Marchal's Conjecture: From the Equilateral Triangle to the Eight

In this talk, we look at periodic solutions of the N-body problem called choreographies. Specifically, we investigate Marchal's conjecture which asserts that the Lagrange equilateral triangle and the figure-eight are in the family of choreographies, known as the P_{12} family. The P_{12} family is characterized by 12 symmetries per period. Once imposed on the level of the Fourier coefficients, we present a rigorous continuation method where the frequency of the rotating frame coordinates plays the role of the parameter. The strategy consists in expanding the periodic orbits as Chebyshev series with respect to the parameter. We rely on a Newton-Kantorovich type argument to prove the branch. Moreover, we show how the present strategy handles the two bifurcations located at both extremities of the desired branch, namely the equilateral triangle and the figure-eight.

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MS168

Global Dynamics and Blowup in Some Quadratic PDEs

Conservation laws and Lyapunov functions are powerful tools for proving the global existence of stability of solutions, but for many complex systems these tools are insufficient to completely understand non-perturbative dynamics. In this talk I will discuss a complex-scalar PDE which may be seen as a toy model for vortex stretching in fluid flow, and cannot be neatly categorized as conservative nor dissipative. In a recent series of papers we have shown that this equation exhibits rich dynamical behavior that exist globally in time: non-trivial equilibria, homoclinic orbits, heteroclinic orbits, and integrable subsystems foliated by periodic orbits. On the other side of the coin, we show several mechanisms by which solutions can blowup. I will discuss these results, and current work toward understanding unstable blowup.

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MS168

Forcing results for travelling waves in a cylinder through CAPs for equilibria

Travelling waves form a prominent feature in the dynamics of scalar reaction-diffusion equations on unbounded cylinders. A topological invariant, based on a Floer homology construction, gives insight into the structure of the solutions of the reaction-diffusion equations. It encodes relations between connecting orbits on the one hand and equilibria, enhanced with (relative) index information, on the other. This leads to forcing theorems for travelling wave solutions. These theorems can be made effective by finding equilibria and their indices through computer-assisted proofs.

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MS168

Optimal Periodic Minimizers to the Ohta-Kawasaki and Swift-Hohenberg Energies

In this talk we use techniques from computer assisted proofs to construct and verify local minimzers for the Ohta-Kawasaki and Swift-Hohenberg energies. We construct solutions in one, two and three dimensions with prescribed crystallographic symmetries and solve for the optimal domain size simultaneously. The Morse index is used to show that all candidate solutions are local minimzers. In two dimensions the periodic solutions are then compared to localized patterns and some with defects. This is joint work with Jan Bouwe van den Berg.

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MS169

Analyzing the 2013-2020 drug overdose mortality wave in the United States

Over the past two decades, drug overdose deaths have dramatically increased in the United States. A first wave of overdoses due to prescription opioids emerged in the 2000s, followed by a wave of heroin induced deaths; the most recent surge in mortality began in 2013 and is primarily driven by fentanyl and methamphetamine use. We examine trends in drug overdose deaths by gender, race and geography in the United States during the third wave, between 2013-2020. To provide insight into the population-level dynamics of drug-overdose mortality, we also develop an age-structured model for drug addiction. We combine our model with overdose fatality data to estimate parameters and forecast the evolution of overdose trends.

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MS169

Pressure-Driven Wrinkling of Soft Inner-Lined Tubes

A simple equation modelling an inextensible elastic lining of an inner-lined tube subject to an imposed pressure difference is derived from a consideration of the idealised elastic properties of the lining and the pressure and soft-substrate forces. Two cases are considered in detail, one with prominent wrinkling and a second one in which wrinkling is absent and only buckling remains. Bifurcation diagrams are computed via numerical continuation for both cases. Wrinkling, buckling, folding, and mixed-mode solutions are found and organised according to system-response measures including tension, in-plane compression, maximum curvature and energy. Approximate wrinkle solutions are constructed using weakly nonlinear theory, in excellent agreement with numerics. Additionally, exact wrinkle solutions and a mapping to a related family of problems are identified, allowing for explicit characterization of the effect of the substrate. Our approach explains how the wavelength of the wrinkles is selected as a function of the parameters in compressed wrinkling systems and shows how localised folds and mixed-mode states form in secondary bifurcations from wrinkled states. Our model aims to capture the wrinkling response of arterial endothelium to blood pressure changes but applies much more broadly.

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MS169

Information Flow in the Basal Ganglia

An interesting and common problem in neuroscience is understanding dynamics that emerge in populations of neurons integrating inputs from multiple sources. This talk will consider this problem in the substantia nigra pars reticulata (SNr), an output region of the basal ganglia (BG), which are a collection of brain regions central to behavioral functions such as decision making and action selection. The SNr receives input from two inhibitory pathways that exhibit very different firing properties. Specifically, this talk discusses two aspects of how the SNr processes these inputs: (1) the impact of chloride regulation and (2) the increase of slow oscillations under dopamine depletion, indicating possible relevance to Parkinsons Disease. We will discuss this through an analysis of a model of the SNr, that is informed through experimental data.

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MS170

Phase Transitions, Heterogeneity, and Coordination in Pancreatic Beta-Cell Networks

The pancreatic islets of Langerhans are responsible for maintaining glucose homeostasis throughout the body. Over recent years, high-speed multi-cellular recordings from pancreatic islets have allowed for the study of coordinated insulin secretion from a network perspective. To this end, we have been developing mathematical models for studying the effects of heterogeneity, spatial non-uniformity, and coupling on the global dynamics of diffusively-coupled lattice networks. In this work, we focus on populations of oscillators with heterogeneous excitability and the impact of their spatial layout on propensity to exhibit globally coordinated dynamics. Moreover, we consider conditions where heterogeneous dynamics arise and the coordination of excitable clusters by effective coupling through less-excitable regions of the lattice. Together, these models provide a framework for studying how nodal and network features derived from pancreatic islet studies may impact on the resulting dynamics. In the future, we will use this framework to study other networks structures, for example directed networks, networks with excitatory and inhibitory links, and networks with heterogeneous structural connectivity (e.g. small-world networks).

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MS170

Non-Smooth Dynamics of Sleep-Wake Regulation: from Circle Maps to Influencing Policy

We all sleep. When we do not get enough sleep, we are grumpy, we are less able to fight off infection, more likely to have an injury in the workplace and perform less well on cognitive tests. Chronic mis-timed or curtailed sleep is associated with many of societies major ailments including cardio-vascular disease, cognitive decline and some cancers. Sleep-wake regulation has been described as the result of the interaction of two fundamental physiological processes which are driven by input from the environment (primarily light). Here, we will discuss the dynamics of the resulting forced nonsmooth coupled oscillator systems. In the simplest scenarios, the models reduce to circle maps with gaps in which saddle-node bifurcations and border collision bifurcations partition the parameter space into different types of behaviour. We will show how we have used models to quantitatively model data on sleep timing in multiple field studies and are using models to inform public policies on daylight saving time and school start times.

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MS170

Bifurcations of Sleep-Wake Patterns Due to Developmentally Associated Changes in the Homeostatic Sleep Drive

Across early childhood development, sleep behavior transitions from a biphasic pattern (a daytime nap and nighttime sleep) to a monophasic pattern (only nighttime sleep). The transition to consolidated nighttime sleep, occurring in most children between 2- and 5-years old, is a major developmental milestone and is believed to be the result of interactions between the developing homeostatic sleep drive and the circadian drive. Using a physiologically based mathematical model of the sleep-wake regulatory network, we incorporate observational and experimental data from preschool-aged participants to determine parameter sets to model average 2-year-old napping behavior and average 5-year-old non-napping behavior. We then vary six age-dependent parameters associated with the homeostatic sleep drive and find this variation to cause bifurcations in the system, capturing the transition from biphasic to monophasic sleep. We determine the individual contributions of this subset of parameters by independently varying their age-dependent developmental trajectories. Through variation of the transition trajectories, we demonstrate different bifurcation sequences representative of various transition timings, transition durations, and transitional sleep patterns. Finally, we consider the influence different patterns of light exposure may have on the bifurcation sequences predicting the transition from napping to non-napping behavior.

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MS171

Bifurcations of Sleep Patterns due to Homeostatic and Circadian Variations in Sleep-Wake Regulation Models

Mathematical models of physiological sleep-wake networks describe sleep-wake regulation by simulating the activity of wake- and sleep-promoting neuronal populations and the modulation of these populations by homeostatic and circadian drives. The resulting systems of ODEs are piecewise-smooth. Motivated by changes in sleep behavior during early childhood, we vary homeostatic and circadian modulation to analyze effects on developmental transitions of sleep-wake patterns, including napping and non-napping behaviors. To identify the types and sequences of bifurcations leading to changes in stable sleep-wake patterns, we numerically compute circle maps representing model dynamics, which are non-monotonic and discontinuous. We find that the average daily number of sleeps exhibits period adding sequences as homeostatic time constants are reduced. Solutions emerge through saddle-node and border collision bifurcations. In models that include rapid eye movement (REM) sleep states, these sequences are disrupted by period-doubling bifurcations and can exhibit bistability. Additionally, variations in the circadian rhythm, as can occur with seasonal changes, modulates bifurcation sequences, leading to direct transitions between napping and non-napping behavior.

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MS171

Entrainment Map Analysis of Social Jet Lag, Non-24-Hour Sleep-Wake Disorder, and Night Shift Work

Entrainment maps are one-dimensional iterated maps for characterizing circadian entrainment that have some advantages over more well-known tools such as phase response curves. Here, we use entrainment maps to study three scenarios where individuals do not entrain to the 24-h light-dark cycle, leading to misalignment of their circadian phase. With regard to social jet lag, we propose a rule of thumb for sleep and wake onset times that minimizes circadian misalignment for teenagers who engage in compensatory catch-up sleep on weekends. In the case of non-24-h sleep-wake disorder, we show why appropriately timed bright light therapy induces entrainment. Finally, with regard to shift work, we explain why reentrainment times following transitions between day and night shifts are asymmetric, and how higher light intensity enables unusually rapid reentrainment after certain transitions.

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MS171

From Data to Models - Circadian Clocks and Zeitgebers

Circadian clocks schedule recurrent biological processes to optimal time points during the day. They originate from transcriptional translational feedback loops, resulting in self-sustained oscillations of the clock component levels in single cells. These circadian rhythms of the clock components and their regulatory targets can synchronize to daily recurring environmental cues, the zeitgebers, resulting in fixed phase relationships to the zeitgebers and equal periods of zeitgebers and circadian rhythms. The dynamics of circadian rhythms can be investigated with mathematical models of the feedback loops. Those models are cell type specific and fitted to periods, amplitudes, and phases of observed circadian rhythms of known clock components. A clinical application of the mathematical modelling of circadian rhythms is the simulation of circadian treatment schedules with multiple zeitgebers. We have shown that there can be optimal phases between two zeitgebers which facilitate the synchronization of the circadian rhythm in a model which was fit to 24h of murine gene expression. Unlike the murine data, clinical human gene expression data is snapshot-like and includes only a single time-point per patient. We show that it is possible to compare circadian rhythms of patient groups and to get phase information of patients circadian rhythms from gene expression data without temporal information, allowing us to fit disease adapted mathematical models of the human circadian clock.

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MS171

Circadian Synchronization Therapy: Personalizing Light Interventions for Patients with Cancer-Related Fatigue

Circadian rhythms underlie far more biological functions than just sleep and wake, but measuring them experimentally is expensive and challenging to scale. Mechanistic mathematical models of circadian rhythms, developed over the last three decades, have recently begun to show promise for non-invasive tracking of rhythms outside the lab, allowing for personalized light therapy interventions to be deployed in real world contexts. Traditional lighting interventions have often focused on using mathematical modeling to generate schedules for phase advancing or delaying users crossing time zones or working night shifts. In this talk, I will discuss preliminary results from a trial of 160 patients with cancer-related fatigue, in which patients were put on algorithm-generated schedules of light and dark aimed both at achieving phase advances and delays where needed, but also at boosting the amplitude of their circadian rhythms through midday targeted bursts of light exposure.

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MS172

Analyzing the Differences in Olfactory Bulb Spiking with Ortho-and Retronasal Stimulation

Flavor perception is a fundamental governing factor of feeding behaviors and associated diseases such as obesity. Smells that enter the nose retronasally, i.e. from the back of the nasal cavity, play an essential role in flavor perception. Previous studies have demonstrated that orthonasal olfaction (nasally inhaled smells) and retronasal olfaction involve distinctly different brain activation, even for identical odors. Differences are evident at the glomerular layer in the olfactory bulb (Gautam et al. 2012, Sanganahalli et al. 2020) and can even be identified in the synaptic inputs to the bulb (Furudono et al. 2013). Why does 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 (Grosmaitre et al, 2007, Iwata et al, 2017). To investigate this, we use computational fluid dynamics to simulate and analyze shear stress patterns during natural inhalation and sniffing. We will show preliminary results demonstrating that shear stress forces differ for orthonasal vs. retronasal air flow; i.e. inspiration vs. exhalation, in a model of the nasal cavity, and connect these findings to our earlier work on directional selectivity in neural network models of the olfactory bulb (Craft et al. 2021).

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MS172

Chaotic Dynamics in Spatially Distributed Neuronal Networks

Neural activity in the cortex is highly variable in response to repeated stimulus. Population recordings across the cortex demonstrate that the variability of neuronal responses is shared among large groups of neurons and concentrates in a low dimensional space. However, the source of the population-wide shared variability is unknown. In this work, we analyzed the dynamical regimes of spatially distributed networks of excitatory and inhibitory populations. We found that networks with similar excitatory and inhibitory projection widths, an anatomical feature of the cortex, can exhibit chaotic spatiotemporal dynamics. The chaotic solutions contain low-frequency power in rate variability and have low-dimensional and distance-dependent correlations, in agreement with experimental findings. In addition, rate chaos can be induced by globally correlated noisy inputs. These results suggest that spatiotemporal chaos in cortical networks can explain the shared variability observed in neuronal population responses.

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MS172

Mathematical Mechanism Underlying Hierarchical Timescales in the Primate Neocortex

In the neocortex, while early sensory areas encode and process external inputs rapidly, higher-association areas are endowed with slow dynamics to benefit information accumulation over time. This recent experimental observation raises the question of why diverse temporal modes are well segregated rather than being mixed up across the cortex, despite high connection density and an abundance of feedback loops. In this talk, I will introduce an anatomically based network model of primate cortex, and show that a hierarchy of temporal response windows along the cortical hierarchy naturally emerges in the model. By mathematically analyzing the primate cortical model, crucial conditions of synaptic excitation and inhibition are identified that give rise to timescale segregation in a hierarchy. Based on this model, I will also discuss the mathematical relation between timescales segregation and signal propagation in the cortex.

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MS172

Neuronal Dynamics of Strong Anticipation in Musical Action

When humans synchronize with a musical stimulus, neural transmission delays and spontaneous rates of activity play a role in the observed asynchronies between human actions and the underlying musical tempo. Here we present two oscillatory dynamical system models of music synchronization, validated with empirical data. The first model explains the systematic human tendency to anticipate a metronomes beats using anticipation mechanisms previously observed in non-biological delayed-coupled systems. This model highlights the role of neural transmission delays in adaptive human synchronization. The second model explains how interpersonal synchronization is affected by an individuals spontaneous rates of movement. It uses behavioral-timescale plasticity mechanisms that adjust the models rate of activity to match a stimulus rate. If the stimulus ceases it returns to its original rate due to an elasticity mechanism. Together, these models demonstrate the theoretical plausibility that transmission delays and spontaneous oscillatory activity play a role in human synchronization behavior with music. Models also make testable predictions, and pave the way for future behavioral research that further validates these mechanisms.

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MS173

Instability of Planar Interfaces in Reaction-Diffusion-Advection Equations

We consider planar interfaces between stable homogeneous rest states in singularly perturbed 2-component reaction diffusion advection equations, motivated by the appearance of fronts between bare soil and vegetation in dryland ecosystems, as well as multi-interface solutions, such as vegetation stripes. On sloped terrain, one can find stable traveling interfaces, while on flat ground, one finds that sideband instabilities along the interface can lead to labyrinthine Turing-like patterns. To explore this behavior, using geometric singular perturbation methods, we analyze instability criteria for planar interfaces in reaction diffusion advection systems, focussing on a specific Klausmeier-type model, and examine the effect of terrain slope on the stability of the interfaces.

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MS173

Topological Arguments in the Stability Analysis for a Front in Rosenzweig - MacArthur Population Model

We consider a diffusive Rosenzweig-MacArthur predator-prey model. For a particular parameter regime it is known that this system supports fronts which are small perturbations of the fronts in a related Fisher-KPP equation. We investigate whether the stability of the fronts is also governed by the scalar Fisher-KPP equation. The techniques of the analysis include a construction of unstable augmented bundles and their treatment as multi-scale topological structures.

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MS173

Traveling Waves and Pulses Arising in a Model of Embryonic Cell Migration and Differentiation

In embryonic development, formation of blood vessels in the retina of the eye is critically dependent on prior establishment of a mesh of astrocytes. Astrocytes emerge from the optic nerve head and then migrate over the retinal surface in a radially symmetric manner and mature from astrocyte precursor cells (APCs) to immature perinatal astrocytes (IPAs) through differentiation. We develop a PDE model describing the migration and differentiation of astrocytes, and we explore the existence of traveling waves and pulses to gain insight on the mechanisms most responsible for the spatial distribution of APCs and IPAs in the embryonic retina.

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MS173

Invasion Fronts Mediated by Alignment and Consumption

In a striking example of collective behavior, swarms of locusts form dense fronts as they move through an agricultural field and consume vegetation. Individual locusts alternately crawl and stop to eat depending on the amount of available food nearby, accounting for the steep front in the density profile of the swarm. Locusts are also known to align their direction of motion with nearby neighbors, resulting in the shared direction of the swarm. These effects (pause-go motion and alignment) are commonly implemented in agent-based models for collective motion. In this talk, we formulate a continuum model with alignment and consumption as driving factors. We study the linear stability of front solutions and discuss the consequences for our understanding of the individual-level mechanisms of locust biology.

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MS175

A Network Model for Orientation in the Drosophila

In a recent paper, Lyu et al. (Nature,2021) described how the drosophila makes vector computations to be able to orientate during flight. The paper refers to both experimental measurements and ODE network models for calcium activity in the fly's brain. In this talk, we will discuss in detail the relevance of the mathematical modeling with respect to the observed experiments.

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MS175

Synchronization in an Externally Stimulated Hodgkin-Huxley Reaction-Diffusion System

In this talk, I will discuss the synchronization phenomenon in a network of Hodgkin-Huxley (HH) Reaction Diffusion (RD) equations. In the model, each neuron communicates with its post-synaptic neurons through the end of its axon, which is represented by a HH RD system. We assume that the synaptic coupling is nonlinear. In the network, three neurons receive an external forced periodic signal. I will discuss relevant numerical simulations in this setting with a specific interest in the synchronization phenomenon occurring in the network as well as the dynamics observed when the frequency of the input signals are varied.

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MS175

Modeling Data from Eeg with Non Autonomous Parabolic and Elliptic Equations

Aphasia is a language disorder that affects the ability to speak. A major cause of aphasia is a stroke in the left side of the brain which controls speech and language. There is a lot of research going on to provide non-invasive brain stimulation treatments to help patients with aphasia. In this talk I will discuss mathematical modeling aspects relevant with respect to EEG collected data in patients with aphasia during specific experiments.

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MS176

Data-Driven Closure Modelling via Stochastic OnsagerNet and Application

Dynamics of complex dissipative systems determine the behaviour of many biological as well as artificial structures. Prominent examples include polymer dynamics, protein folding and unfolding, electrical signal propagation in organs, molecular self-assembly and the behaviour of glassy 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. First, I will introduce how to choose the macroscopic coordinates such that they can satisfy a closed dynamical system. Second, I will introduce how to construct stochastic OnsagerNet to learn stochastic dynamics. 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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MS176

Low-Resolution Image Prior Based Network for Limited-Angle CT Reconstruction

Low-resolution image prior based network for limited-angle CT reconstruction In the practical applications of computed tomography imaging, the projection data may be acquired within a limited-angle range and corrupted by noises due to the limitation of scanning conditions. The noisy incomplete projection data results in the ill-posedness of the inverse problems. Based on the observation that the low-resolution reconstruction problem has better numerical stability, we propose a novel low-resolution image prior based CT reconstruction model for limited-angle reconstruction.More specifically, we build up a low-resolution reconstruction problem on the down-sampled projection data, and use the reconstructed low-resolution image as prior knowledge for the high-resolution limited-angle CT problem. The constrained minimization problem is then solved by the alternating direction method with all subminimization problems approximated by the convolutional neural networks. Numerical experiments demonstrate that our double-resolution network outperforms both the variational method and popular learning-based reconstruction methods on noisy limited-angle reconstruction problems.

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MS176

Random Matrix Methods for Machine Learning: Lossless Compression of Large and Deep Neural Networks

Title: Random Matrix Methods for Machine Learning: Lossless Compression of Large and Deep Neural Networks Abstract: The advent of the Big Data era has triggered a renewed interest in large-dimensional machine learning (ML) and deep neural networks (DNNs). These methods, being developed from small-dimensional intuitions, often behave dramatically different from their original designs and tend to be inefficient on large-dimensional datasets. By assuming both dimension and size of the datasets to be large, recent advances in random matrix theory (RMT) provide novel insights, allowing for a renewed understanding and the possibility to design more efficient machine learning approaches, thereby opening the door to completely new paradigms. In this talk, we will start with the curse of dimensionality phenomenon in high dimensions, and highlight how these counterintuitive phenomena arise in ML practice when large-dimensional data are considered. By focusing on the concrete problem of compressing both shallow and deep neural networks, we show how the proposed theory can be applied to design efficient DNN compression schemes with strong performance guarantee.

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MS176

Neural Network Stochastic Differential Equation Models with Applications to Financlal Data Fore-

casting

In this article, we employ a collection of stochastic differential equations with drift and diffusion coefficients approximated by neural networks to predict the trend of chaotic time series which has big jump properties. Our contributions are, first, we propose a model called Lévy induced stochastic differential equation network, which explores compounded stochastic differential equations with α-stable Lévy motion to model complex time series data and solve the problem through neural network approximation. Second, we theoretically prove that the numerical solution through our algorithm converges in probability to the solution of corresponding stochastic differential equation, without curse of dimensionality. Finally, we illustrate our method by applying it to real financial time series data and find the accuracy increases through the use of non-Gaussian Lévy processes. We also present detailed comparisons in terms of data patterns, various models, different shapes of Lévy motion and the prediction lengths.

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MS177

Mathematical Assessment of the Role of Pre-Exposure Prophylaxis on the HIV Pandemic

The use of pre-exposure prophylaxis (PrEP), where approved antivirals are administered to uninfected high-risk individuals, is universally regarded as a promising strategy to prevent susceptible high-risk individuals from acquiring HIV infection from their infected partners. A number of antiviral drugs (and their combinations) have been developed and are being used as prophylaxis against the HIV/AIDS pandemic globally. This talk presents a mathematical model, which takes the form of a deterministic system of nonlinear differential equations, for assessing the population-level impact of the use of PrEP in an MSM (men-who-have-sex-with-men) population. The asymptotic stability properties of the equilibria of the model, as well as characterization of the bifurcation types the model undergoes, will be discussed. Theoretical conditions for the effective control or elimination of the disease in the MSM population will be derived.

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MS177

Quantifying Dynamics of Time Irreversible Markov Chains with Application to a Gene Regulatory Network

Markov chains are among the most well-known and established probabilistic models. An important arsenal of tools for analysis of transitions taking place in Markov chains is offered by the transition path theory (TPT). TPT studies the statistical properties of reactive trajectories which are those trajectories by which a random walker transits from one subset in the state-space to another disjoint subset. This transition process is described by the so-called effective current. Time-irreversible Markov chains often arise in biological models, for example in gene regulatory networks. However, if the Markov chain is irreversible, the effective current is an inadequate description of the transition process where elementary cycles of length greater than two are present. We develop analytical and computational tools based on TPT in order to quantify the dynamics in time-irreversible Markov Chains. These tools are applied to a gene regulatory network modeling the dynamics of the Budding Yeast cell cycle.

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MS177

A Within-Host Model for the Pharmacokinetics and Pharmacodynamics of Malaria

Malaria is a significant public health concern, especially as the increasing presence of drug resistance creates challenges for control efforts. Over the last several decades, mathematical modeling has been used to gain insight into the within-host dynamics of malaria parasites. Within the human host, the parasite undergoes several life stages, including an asexual replication stage associated with the onset of symptoms, and a sexual stage of parasites (the gametocytes) which can be transmitted to mosquitoes. Of particular importance is the incorporation of pharmacokinetics and pharmacodynamics to better understand how different actions of treatment on malaria parasites impact gametocyte levels and the potential to select for drug-resistant parasites. In this talk we discuss a within-host model that incorporates anti-malarial treatment and explore the impact of different dosing regimes and drug actions on parasite load and probability of forward transmission.

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MS177

Linking Temperature to Malaria - A Mathematical Conversation

The abundance and redistribution of mosquitoes that transmit diseases have been reported to be affected by shifting climatic patterns. In particular, mosquito biting rate, adult mortality rate, vector competence, and mosquito blood seeking cycle, its gonotrophic cycle, are all malaria transmission factors/parameters impacted by temperature. Likewise, parasite development within the mosquito, from ingested parasite to the formation of the transmissible parasite forms of the parasite, sporozoites, are affected by temperature. In this talk, I will discuss how linking temperature-dependent mosquito and parasite traits to regional temperature, without a sinusoidal fit, can be exploited for a more region-specific temperature-dependent parasite and malaria indicator estimation.

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MS178

Global Sobol Sensitivity Analysis and Its Application to Triple Negative Breast Cancer Combination

Chemotherapies

Triple-negative breast cancer (TNBC) is a heterogenous disease that is defined by its lack of estrogen hormone, progesterone hormone and human epidermal growth factor receptor 2 (HER2). The lack of receptors frequently results in poorer outcomes, higher rates of metastasis and recurrence since there are no viable targeted therapies. Combination chemotherapy treatments, radiation therapies, and surgery are the current standard-of-care for TNBC. We have built an ordinary differential equation model of TNBC and its response to a combination of chemotherapies, doxorubicin (DRB) and paclitaxel (PTX). This model was parameterized to longitudinal tumor volume and proliferation data, then validated using percent necrosis data for both a human cancer mouse model (MDA-MB-231) as well as a syngeneic, mammary carcinoma (4T1) mouse model. This novel mathematical model can give insight to the ordering, dosing, and timing of DRB and PTX treatment. More importantly, this model can also give insight to vital immunotherapies for TNBC, that we would not otherwise receive, due to its calibration to the syngeneic, mammary carcinoma (4T1) mouse model.

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MS178

Mathematical Models of Infectious Diseases – Consequences of Underlying Assumptions

Mathematical models have been used to study various disease transmission dynamics and control for epidemics. Many of these studies are based on SEIR- types of compartmental models with exponentially distributed stage durations. We examine the underlying assumptions made in some of these model and present examples to illustrate the potential issues associated with these assumptions in terms of model evaluations of control and intervention strategies.

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MS178

Towards A Modeling Framework for Pediatric Sickle Cell Pain

Sickle cell pain presents in acute episodes in pediatric patients, as opposed to the chronic pain observed in adults. The episodic nature of pain events in pediatric patients necessitates a distinct approach from what has been used to mathematically model pain severity levels in adults. Statistical studies have examined interactions between sleep actigraphy measurements — like sleep quality and sleep efficiency — and pain levels in pediatric populations, and we propose a framework for modeling pediatric pain dynamics that incorporates the effects of sleep actigraphy and electronic survey data over varying time windows. We hypothesize that cumulative effects of these measurements will be more important than daily measurements in both replicating pain severity levels and determining markers of a pain episode. The ability to identify markers preceding the onset of a pain episode will be crucial in improving patient quality of life. We present work in progress towards developing this modeling framework.

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MS178

Optimal Timing of Steroid Initiation in Response to CTLA-4 Antibody in Metastatic Cancer: A Mathematical Model

Immune checkpoint inhibitors, introduced in recent years, have revolutionized the treatment of many cancers. However, the toxicity associated with this therapy may cause severe adverse events. In the case of advanced lung cancer or metastatic melanoma, a significant number (10%) of patients treated with CTLA-4 inhibitor incur damage to the pituitary gland. In order to reduce the risk of hypophysitis and other severe adverse events, steroids may be combined with CTLA-4 inhibitor; they reduce toxicity, but they also diminish the anti-cancer effect of the immunotherapy. This trade-off between tumor reduction and the risk of severe adverse events poses the following question: What is the optimal time to initiate treatment with steroid. We address this question with a mathematical model from which we can also evaluate the comparative benefits of each schedule of steroid administration. In particular, we conclude that treatment with steroid should not begin too early, but also not very late, after immunotherapy began; more precisely, it should start as soon as tumor volume, under the effect of CTLA-4 inhibitor alone, begins to decrease. We can also compare the benefits of short-term treatment of steroid at high doses to a longer-term treatment with lower doses.

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MS179

A Mathematical Approach to Variations in Ovulatory Function

A normally functioning ovulatory cycle results from a tightly regulated system of crosstalk between the brain and the ovaries. Failure to regulate reproductive hormones may cause ovarian dysfunction and sometimes infertility. Polycystic ovary syndrome (PCOS) is a relatively common cause of such dysfunction, which is often accompanied by irregular glucose metabolism. Here we examine mechanisms of disruption and characterize ovulatory phenotypes through a new endocrine model and discuss the impact of metabolic abnormalities on the female endocrine system.

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MS179

Skateboard Tricks and Topological Flips

We study the motion of skateboard flip tricks as continuous curves in the matrix group SO(3). We show that up to continuous deformation there are only four flip tricks. We will also present numerical simulations using the classical analytic solutions and the Runge-Kutta-Munthe-Kaas Lie group integrator. Finally we will present animations and visualizations developed in Python for this project.

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MS179

Dynamics of Flow-Kick Disturbance Models

To incorporate ongoing disturbances into a differential equation (DE) model of ecological processes, one might embed the disturbance continuously in the DE or resolve the disturbance discretely. For example, do harvests from a logistic population appear continuously as x = x(1 - x) - h(x) or do individual harvests periodically kick the state x as it flows according to x = x(1 - x)? In this talk well describe the flow-kick approach to modeling repeated, discrete disturbances and explore the dynamic implications of this modeling choice. Well position continuous disturbances as limits of repeated, discrete ones and describe how flow-kick systems both mimic and depart from their continuous analogs.

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MS179

Maximally Mixing Braids And Their Physical Realization In Active Nematic Systems

The Nielsen-Thurston classification theorem establishes a deep connection between braids and surface dynamics. We consider braids on low-genus surfaces, with braid generators defined using maximally symmetric embedded graphs. Using a recently developed algorithm, we find unique pseudo-Anosov (pA) surface braids which maximize a suitably normalized version of the braid dilation (or equivalently the topological entropy). In particular, we will report on an interesting family of these maximally mixing braids which includes the well known golden and silver ratio Artin braids. Furthermore, we will introduce a physical system of active nematic microtubules, which realizes these braids as an emergent property of its dynamics.

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MS180

A Computational Approach to Predict the Outcome of Liver Injury Due to Acetaminophen Overdose: Exploring Biomarkers and Inclusion of Protein Adduct

In the United States, acetaminophen (APAP) overdose is the leading cause of acute liver injury. The current model for assessing liver health, The Kings College Criteria (KCC), cannot predict APAP dosage or time of overdose. The Model for APAP-Induced Liver Damage (MALD) uses dynamic system of differential equations to model liver injury. It applies three bio-markers aspartate aminotransferase (AST), alanine aminotransferase (ALT), and international normalized ratio (INR) to estimate the dosage and the time of overdose to determine if treatment with N–Acetylcysteine (NAC) is sufficient or if patient survival requires a liver transplant. These biomarkers indicate hepatocyte death but are not specific to APAP. We aim to improve the predictive quality of MALD by adding a very effective bio-marker specific to liver injury due to APAP overdose, APAP-protein adduct. We validate our model using a new data set of 59 cases from the Acute Liver Failure Study Group and found the inclusion of APAP-protein adducts in the model improves the ROC curve of MALD by 13.63%. When patients with recorded alcohol use were removed from the analysis, the addition of APAP-protein adducts improved the ROC curve of MALD by 34.22%. We also perform sensitivity analysis of the important parameters associated with the updated model.

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MS180

Machine Learning for Predicting the Dynamics of Infectious Diseases During Travel Through Physics Informed Neural Networks: a Stochastic Approach

We present an application of Stochastic Disease-Informed Neural Networks through deep learning and its application to real data. We show how the approaches can predict the behavior of a disease described by compartmental models that include parameters and variables associated with the movement of the population between neighboring cities, incorporating the stochasticity in the model to obtain precise estimates. Our model validates real data and shows the performance of Physics-Informed Neural Network-based methods to predict the optimal parameters of the proposed model.

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MS180

Application of Machine Learning to Predict Dynamics of Epidemiological Models That Incorporate Human Behavior

Understanding the early transmission dynamics of infectious diseases such as COVID-19 has made us to re-envision how we mathematically model, analyze and simulate the spread of infectious diseases and evaluate the effectiveness of non-pharmaceutical control measures as important mechanisms for assessing the potential for sustained transmission. There have been several works recently showing how differential equations can be learned from data, as well their parameters. A novel and powerful approach is Physics-Informed Neural Network (PINNs) that has been applied successfully to understand system-biology and spread of infectious diseases. In this work, we present modeling, analysis and simulation of a mathematical epidemiological model which incorporates human social, behavioral, and economic interactions. We discuss how these approaches are capable of predicting the dynamics of a disease described by modified compartmental models that include parameters, and variables associated with the governing differential equations. However, human behavior is modelled as stochastic variables which are included in the compartmental models.. Through benchmark problems, we will show that our model validates real-data and demonstrate how such PINNs based methods can predict optimal parameters for a given dataset.

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MS180

Predicting the Outcome of Liver Injury Due to Ischemia Using Computational Models with Real Time Patient Data

Ischemic Hepatitis (IH) is a liver injury preceded by hepatocyte death. The only way to diagnose this disease is to eliminate the possibilities of all other liver injuries currently. To combat this issue, our goal is to explore computational models that are able to predict the outcome in terms of death or survival of a person who suffers from IH based on various biomedical indicators such as: creatinine peak, international normalized ratio peak, aspartate aminotransferase peak, alanine transaminase peak, and bilirubin peak. The real patient data was collected across multi centers from the US by the Acute Liver Failure Study Group. We clean, process, and analyze the data utilizing classification models like logistic regression and regression tree method, including BART, to predict the outcome of the patients suffering from IH. We then apply SMOTE and boosting techniques to improve the prediction accuracy. Obtaining the sensitivity and specificity of the testing methods helps us compare the outcome to determine the best model.

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MS181

Actin-Myosin Dynamics During Bleb Stabilization

The actin cortex is very dynamic during cell migration. When cells move using pressure driven leading-edge protrusions of their membrane (blebbing), they reform the cortex within a new bleb and completely disassemble the old cortex in the region devoid of the cell membrane (actin scar). The regulation of this process, referred to as bleb stabilization, is not fully understood. Our present work investigates the role of Myosin motor proteins, which have been shown to be necessary for blebbing, on actin dynamics during stabilization. Analysis of microscopy data from protein localization experiments inDictyostelium discoideum cells reveals a local accumulation of myosin in the actin scar prior to a significant disassembly of the cortex. A mathematical model of actin-myosin dynamics, developed and analyzed to explain our experimental observations, shows that the accumulation of myosin in the actin scar is a robust mechanism that mediates the onset and duration of cortex degradation during bleb stabilization.

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MS181

Widespread Ecological Networks and their Dynamical Signatures (WENDyS)

It has become more and more pertinent to study the fates of communities of species, especially with the presence of climate change and anthropological disturbances. To do so, theoretical ecologists have often modeled communities' demographic behavior with ordinary differential equations. These have lended valuable insight into possible fine-scale dynamics that can occur between multiple species. Yet, as the number of species, interactions, and complexity of those interactions grow within such models, the more challenging it is to find analytical solutions to them. Furthermore, these additions typically introduce more unknown variables (parameters) into the system: while one choice of parameters may lead to one set of qualitative solutions, another choice could lead to entirely different dynamics. The higher dimension this parameter space is, the more infeasible it is to theoretically or numerically explore the long-term behaviors of interacting species. To show how we can overcome this hurdle, I will introduce a new mathematical framework, Widespread Ecological Networks and their Dynamical Signatures (WENDyS). Here, we will take a step back from fine-scale dynamics. I will instead show how we can use WENDyS to take a community and its interactions and translate them into a set of simple, coarse-scale population growth models. Here, we output a library of all possible population dynamics within the community. Each set of dynamics is generated by different relative orderings of variables that parameterize these models. In other words, by foregoing fine-scale details, we can explore all of parameter space at once and output all possible long-term dynamics of a community of species.

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MS181

Effects of Data Availability on Assessments of Identifiability for An Seir Model

When using biological data to parameterize and study mathematical models, it is important to understand the limitations of available data for reliable parameter recovery. For example, epidemiological data may become available gradually alongside an emerging infection, be collected over wide time intervals, or report quantities that do not directly align with model states. One approach to assessing the suitability of data for parameter estimation is by studying the identifiability of a parameter estimation problem. However, there are different means of assessing identifiability, both in theory and in practice, which may lead to different conclusions. In this work, we consider an SEIR infection model with three unknown parameters and compare assessments of parameter identifiability for a variety of assumed data. We explore the effect of different observed states (infections, incidence, and cumulative incidence) as well as different temporal resolutions in the data. We compare the resulting parameter identifiability using both Monte Carlo simulations and correlation matrices, which give different results in most cases. These findings help us understand the conditions under which we consider a parameter to be identifiable, and how such conclusions depend on the underlying methods for quantifying identifiability.

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MS181

A Pulsed Model of Drug Resistance in Soil-Transmitted Helminths

Soil-transmitted helminths cause a significant health burden, infecting more than 1.5 billion people worldwide. The World Health Organization is implementing periodic mass drug administration to combat these parasitic worms. However, there is an increased risk for the development of drug resistance as a higher fraction of the population is treated at a higher frequency. While there is little evidence for resistance in human helminth species, resistance in livestock helminths is common and modeling in this context has provided useful management recommendations. Because drug resistance in human helminths could have devastating consequences for our ability to treat the disease, we need a better understanding of how drug administration can influence population dynamics and resistance evolution. We develop and analyze a pulsed model for drug resistance evolution, parameterized using data on three human helminths and three livestock helminths to study the effects of 1) drug treatment timing and coverage and 2) host and parasite organism biology. We analytically solve for a critical frequency at which treatment leads to parasite elimination and we identify parasite and host traits that have the greatest impact on the helminth population dynamics and the speed of resistance evolution.

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MT1

Spatial Patterns in Nature: An Entry-Level Introduction to Their Emergence and Dynamics

See overall session abstract.

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MT1

Spatial Patterns in Nature: An Entry-Level Introduction to Their Emergence and Dynamics

See overall session abstract.

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MT2

Spatial Patterns in Nature: An Entry-Level Introduction to Their Emergence and Dynamics - Part II

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MT2

Spatial Patterns in Nature: An Entry-Level Introduction to Their Emergence and Dynamics - Part II

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MT3

Topological Signal Processing for Dynamical Systems

See overall session abstract.

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MT4

Topological Signal Processing for Dynamical Systems

See overall session abstract.

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PP1

Optimizing Oscillators for Specific Tasks Predicts Preferred Biochemical Implementations

Oscillatory processes are used throughout cell biology to control time-varying physiology including the cell cycle, circadian rhythms, and developmental patterning. It has long been understood that free-running oscillations require feedback loops where the activity of one component depends on the concentration of another. Oscillator motifs have been classified by the positive or negative net logic of these loops. However, each feedback loop can be implemented by regulation of either the production step or the removal step. These possibilities are not equivalent because of the underlying structure of biochemical kinetics. By computationally searching over these possibilities, we find that certain molecular implementations are much more likely to produce stable oscillations. These preferred molecular implementations are found in many natural systems, but not typically in artificial oscillators, suggesting a design principle for future synthetic biology. Finally, we develop an approach to oscillator function across different reaction networks by evaluating the biosynthetic cost needed to achieve a given phase coherence. This analysis predicts that phase drift is most efficiently suppressed by delayed negative feedback loop architectures that operate without positive feedback.

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PP1

Finite Element Solution of Time-Dependent Compressible Navier-Stokes Equations

In the real situation, most fluid flow problems are described by Navier-Stokes equations, which are systems of nonlinear partial differential equations. The non-linearity is caused by convective acceleration, which is an acceleration associated with the change in velocity in time. It is very difficult to describe and analyze most problems because of non-linearity that makes them impossible to solve. However, if the Navier-Stokes equations are solved, they can also be used to describe and analyze more complex materials and fluid flow problems. The numerical solution of Navier-Stokes equations can be carried out using several different approaches at present, including finite difference, finite volume, and finite element methods. In this poster work, we intend to solve the time-dependent compressible Navier-Stokes equations with energy equations in a unit square cavity. For simplicity, assume that pressure satisfies the isentropic state equation. The governing partial differential equations system is solved by a finite element method with no-slip boundary conditions. The Euler backward method is applied for time discretization and the finite element method is for space discretization. The experimental order of convergence and numerical results will be discussed.

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PP1

Blowing-Up Nonautonomous Vector Fields

The blow-up method has turned out to be a powerful technique to desingularize vector fields around non-hyperbolic equilibria. Originating in algebraic geometry to analyze singularities of algebraic varieties, this technique was later transferred to autonomous differential equations. It uses a non-injective transformation that maps a higher-dimensional object onto the non-hyperbolic equilibrium constituting the singularity. The dynamics on this larger, blown-up version of the singularity may then be desingularized using suitable time reparametrization. We extend this method to non-autonomous equations, which transforms the original, finite dimensional ordinary differential equation into an infinite-dimensional delay equation with infinitely growing delay, but hyperbolic structure. For a class of planar, asymptotically autonomous differential equations that have equilibrium solutions with zero Lyapunov spectrum we show the existence of nonautonomous invariant manifolds. These correspond to the stable and unstable manifold of a desingularized, infinite-dimensional equation that we obtained by using the blow-up method. Furthermore, we outline how an iteration of the blow-up procedure allows to desingularize more general vector fields.

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PP1

Interpretable Feature Selection for Decoding Context in the Amygdala

The amygdala is known to be responsible for extracting from external stimuli their social and emotional significance. Contextual changes, which generally take place over longer timescales than stimuli, are crucial to determining this social importance. It is not known how the amygdala encodes social significance. One way the amygdala might encode these persistent states is through context-dependent network dynamics within and between amygdala nuclei. To examine this possibility, we analyze local field potential (LFP) data recorded from non-human primate amygdala in which the subjects are presented with alternating blocks of social and non-social tactile stimuli. We trained a deep convolutional neural network to classify spectrograms of baseline (inter-stimulus) LFP activity by experimental block type (social vs. non-social). Results show that context can be reliably decoded from baseline LFP in amygdala, regardless of nuclei region and provides evidence of distinct context-dependent brain states. We also explore the use of GRAD-CAM and other probative tools in an attempt to improve model interpretability and thereby our understanding of neural mechanisms for encoding & decoding social significance.

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PP1

Flocking in Constrained Geometry Using Dynamic Mode Decomposition

Multi-agent dynamical systems have many degrees of freedom, but they may exhibit emergent behaviors that are much lower dimensional. Such systems are observed in natural and artificial systems, such as bird flocks and communication networks. Decades of literature have proposed mathematical models of such complex systems from analyzing local agent-to-agent interactions. In almost all of previous work, the geometry of the domain where the dynamics occur is at most constrained at the boundaries. However, we know that complex geometries can affect individual behavior by limiting the phase space, such that the geometry effectively can induce or exclude interactions that are usually not possible without confinement. Previous work on the study of obstacles on the Vicsek flocking model has shown that adding obstacles to the domain acts to confound the agents' aligned motion, and thus global order in the system as measured by traditional parameters. Here, we use Dynamic Mode Decomposition–a novel data-driven approach to study low-order behavior–to explain the tradeoffs between individual and collective behavior when obstacles are present, and the resulting transitions between order and disorder.

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PP1

Novel Mathematical Models for Fate Selection in Neural Crest Stem Cells

The development of an embryonic cell is often conceptualized as similar to a ball rolling down a potential landscape in genotypic space, in which 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 decision points where the cell fate is selected. Historically there are two alternative views of fate specification in neural crest stem cells: the Direct Fate Restriction (DFR) and Progressive Fate Restriction (PFR) hypotheses. In the language of nonlinear dynamics, DFR corresponds to a single stationary bifurcation from which many new stable equilibria arise, while PFR corresponds to a sequence of stationary bifurcations in which intermediate ('partially fate-restricted) states arise before final fate choice is made. Here, employing tools from equivariant bifurcation theory, we discuss the role of symmetry in organising fate restriction. We introduce a novel dynamical model which generically exhibits a Hopf bifurcation and thereby suggests a new, unifying possibility which we term Cyclical Fate Restriction (CFR). We explain how temporal oscillations in gene expression provide a plausible mechanism for the transition from multipotent progenitors to fate-specified cells, and we relate our findings to recently published and ongoing in vivo experiments using the zebrafish neural crest.

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PP1

Dynamics of Inertial and Non-Inertial Particles in Geophysical Flows

We consider the dynamics of inertial and non-inertial particles in a single-layer, quasi-geostrophic (QG) ocean model. We investigate the underlying structures of the flow field by examining the Lagrangian coherent structures (LCS) which are found by computing finite-time Lyapunov exponents (FTLE). We study the behavior of massless non-inertial particles using the fluid velocity fields from the QG model and compare it with the behavior of massless inertial particles in a double-gyre model. For inertial particles with finite size and mass, we use the Maxey-Riley equation to describe the particles' motion, and compare the particles' behavior in a QG flow with their behavior in a double-gyre flow. We explore the preferential aggregation of inertial particles and demonstrate how particle clustering depends on the density ratio, the Stokes number and particle size. We also study the role of the western boundary layer in particle aggregation for the QG model.

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PP1

Semi-Analytical Computation of Heteroclinic Connections Between Center Manifolds with the Parameterization Method

This poster presents methodology for the computation of whole sets of heteroclinic connections between iso-energetic slices of center manifolds of center × center × saddle fixed points of autonomous Hamiltonian systems. It involves: (a) Computing Taylor expansions of the center-unstable and center-stable manifolds of the departing and arriving fixed points through the parameterization method, using a new style that uncouples the center part from the hyperbolic one, thus making the fibered structure of the manifolds explicit. (b) Uniformly meshing iso-energetic slices of the center manifolds, using an novel strategy that avoids numerical integration of the reduced differential equations and makes an explicit 3D representation of these slices as deformed solid ellipsoids. (c) Matching the center-stable and center-unstable manifolds of the departing and arriving points in a Poincar section. The methodology is applied to obtain the whole set of iso-energetic heteroclinic connections between the center manifolds of L_1 and L_2 in the Earth-Moon circular, spatial Restricted Three-Body Problem, for 9 increasing energy levels that reach the appearance of Halo orbits in both L_1 and L_2. Some comments are made on possible applications to space mission design.

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PP1

Modelling Adaptive Cancer Treatment Using Game Theory and Eco-Evolutionary Dynamics

In cancer treatment, it has been shown that improving chemotherapy by combining it with immunotherapy can further slow down the tumour growth compared to chemotherapy alone. However, it is not clear if there exist optimal combined treatment strategies that could further slow down or possibly stop the tumour growth. To address this question, we propose a game-theoretic model of eco-evolutionary dynamics in the form of stochastic differential equations. The model captures: carcinogenesis (the onset of cancer) and subsequent cancer growth, incorporates the effects of chemotherapy and immunotherapy, and is capable of reproducing clinical data. Analysis of nonlinear dynamics of the model reveals instabilities that could help design "Adaptive Therapy Treatments for Cancer" that are both less invasive and more effective.

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PP1

Exploring Temporal Pulse Replication in the Fitzhugh-Nagumo Equation

In 2018, Carter and Sandstede made use of geometric singular perturbation theory and blow-up analysis to determine the mechanism behind parametric pulse replication in the Fitzhugh-Nagumo equation: the presence of a canard point in the associated traveling-wave ODE leads to the existence of a one-parameter family of solutions the authors termed a homoclinic banana. As one travels along the banana, a transition occurs from single-pulse solutions to double pulses, with an intermediate phase of single pulses with oscillatory tails. As is typical with canard points, this transition takes place in an exponentially thin region of parameter space. Subsequently, in 2021 Carter et al. numerically observed the phenomenon of temporal pulse replication: starting with an initial condition close to a one-pulse on the banana causes the associated solution to mimic the parametric transition dynamically, despite the parameters being fixed. The authors speculated that the parametric transition may generate a nearby invariant manifold which guides the temporal transition. In this talk, we discuss the accompanying stability results for the parametric transition, why those results preclude a simple resolution of temporal pulse replication, and the numerical explorations carried out to address these challenges.

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PP1

Early Warning Signs for Heterogeneous Bistable SPDEs

The use of stochastic partial differential equations (SPDEs) is a powerful tool for the simulation of real-life scenarios, such as phenomena related to climate. When treating systems that present a bifurcation parameter, the study of early warning signs to such event is therefore important. The applications on which such theory is often involved display complex structures with regions in space characterized by different sensibilities. For such reason the introduction of a heterogeneous component in the system can be compulsory for its proper simulation. The poster presented displays results on the study of certain bistable equations, such as the Chafee-Infante type dependent on a bifurcation parameter, on an interval with Dirichlet boundary conditions. The system is then perturbated by a term heterogeneous in space and a Q-Wiener process. The assumptions on the noise are chosen in order to permit a better approximation of real phenomena. Most important is the description of early warning signs for the crossing of the pitchfork bifurcation threshold, as extreme of the possible values assumed by the finite time Lyapunov exponent on a particular solution and as variance along sensible directions for the linearized system.

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PP1

Dynamics Organized by a Symmetric Heteroclinic Cycle in a 4D Model of An Optical Ring Resonator

Micro-resonators are optical devices that can trap and manipulate light for use in applications such as optical storage and signal processing. We consider a micro-resonator that supports two interacting counter-propagating fields of light, generated by two laser beams of equal properties. Mathematically, this system is modeled by a four-dimensional $\mathbb{Z}_2$-equivariant vector field with strength and detuning of the input light as parameters. We identify a symmetric pair of heteroclinic cycles as an organizing centre in the parameter plane. Different types of dynamics nearby are determined by means of continuation of global bifurcations in combination with the computation of kneading invariants and Lyapunov exponents. In this way, we provide a numerical unfolding of this codimension-two global bifurcation, and show how it involves infinitely many further global bifurcations. Apart from its interest from the dynamical systems point of view, our results provide a road map that may help guide experimental studies to find exotic behaviour in this or similar optical systems.

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PP1

Navier Slip Boundary Conditions for Two Dimensional Boussinesq Equations

The Boussinesq approximation describes a fluid that is driven by buoyancy forces arising from differences in temperature. For the velocity field often times no-slip or free-slip boundary conditions are used. In this poster we study the Navier-slip boundary conditions in two dimensions, which interpolate between the no-slip and the free-slip case. The main focus is on regularity results and bounds on the ratio between convective and conductive heat transport, given by the Nusselt number, with respect to the Rayleigh number, describing the strength of the buoyancy force.

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PP1

Chaotic Intracellular Dynamics in a Conductance Neuronal Model

We report the presence of chaotic dynamics in a modified version of the Plant model. The model exhibits three characteristic types of voltage activity: tonic-spiking, bursting, and hyperpolarized quiescence. Two bifurcation parameters are added to the original conductance based model to control the slow dynamics, which are responsible for modulating spiking activity. A bifurcation diagram of the model with these parameters is presented. A transition route from tonic-spiking to bursting activity begins with a saddle-saddle bifurcation and is followed by an adjacent region of transitional chaos. Transitioning from a stable equilibrium state, representing the neural quiescence, to bursting passes through a Andronov-Hopf bifurcation curve with a codimension-two Bautin point. On the left of the Bautin point, the bifurcation is a subcritical causing an onset of complex bursting with chaotic subthreshold oscillations or with unpredictably varying trains of spikes, or both, while on the right it is supercritical giving rise to small subthreshold oscillations morphing into large bursting. Finally, in the bursting region there is presence of spike-adding chaos at transitions between periodic attractors.

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PP1

An Error Function, Data Augmentation, and Visualization for Fitting Voltage Time Series

Central pattern generators (CPGs) are biological neural circuits that produce rhythmic outputs without rhythmic input. We developed a detailed mathematical model of the CPG that controls the swimming behaviors of the sea slug Melibe leonina. The math-CPG can produce a network bursting with specific rhythmic patterns and realistic responses to perturbations recorded in the bio-CPG. We examine the dynamic properties of the Plant model in a slow variable plane. Our blended system that uses electrophysiological recordings to train and optimize the computational model of the Melibe swim CPG using an error functino that captures the rhythmic characteristics of a voltage time series. We also propose using parallel coordinates to visualize the high-dimensional parameter space as well as proposing a form of data augmentation that can be used to prevent overfitting when optimizing with limited data.

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PP1

Dynamics of the Predator-Prey System, Taking into Account the Lower Critical Density of Prey

Populations and Intraspecific Competition

The presented work is devoted to a qualitative-numerical study of the generalized Volterra-Lotka model of the predator-prey system. We additionally introduce intrapopulation and interpopulation factors of population interaction into the classical Volterra model. Taking into account the above factors, the model is described by a system of two ordinary differential equations depending on four parameters in dimensionless variables.The study of the system showed that the model predicts the possibility of four different modes of behavior of the system dynamics: 1) With a low adaptability of the predator to the prey, the predator population always dies out; 2) With an increase in fitness, a stable stationary coexistence of a predator with a prey is possible; 3) Coexistence of populations is possible only in self-oscillatory mode, and the amplitude of oscillations is the greater, the higher the adaptability of the predator, 4) If the adaptability of the predator is too high, both populations are doomed to extinction under any initial conditions.

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PP1

Three-Dimensional Horseshoes and Orientation Reversal in Wild Chaos

Wild chaos is a new type of dynamics with certain robustness properties that can arise in diffeomorphisms of dimension at least three. An important ingredient in this context is a blender: a hyperbolic set with invariant manifolds that appear to be higher-dimensional than expected. The existence of a blender may imply the robust presence of complicated global connections between different parts of phase space. What does a blender actually look like and how does it appear or disappear? We consider a Hénon-like family of maps that exhibits a blender generated by a three-dimensional horseshoe. We investigate how the orientation properties of the map affect the structure of the blender by employing advanced numerical techniques to compute the stable or unstable manifolds of the hyperbolic set in a compactified phase space. This allows us to characterise geometric differences, which are important for how blenders lose their defining properties as parameters change.

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PP1

Hamiltonian Systems and Period Function with Applications

In this work, we develop a constructive procedure to obtain the Taylor expansion, in terms of the energy, of the period function for a non-degenerated center of any planar analytic Hamiltonian system. We apply it to several examples, including the whirling pendulum and a cubic Hamiltonian system. The knowledge of this Taylor expansion of the period function for this system is one of the key points to study the number of zeroes of an Abelian integral that controls the number of limit cycles bifurcating from the periodic orbits of a planar Hamiltonian.

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PP1

Secondary Bifurcations in a Next Generation 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 seizures. Fast rhythmic spikes during the tonic stage are associated with muscle stiffness that give way to bursts and slow waves associated with muscle jerks during the clonic phase. This has previously been theorised to arise in systems with an instability from one temporal rhythm to another via a quasiperiodic transition. We show this is possible in a field version of a new class of neural mass model and that this can arise via a secondary instability of the homogeneous steady state. The bifurcation diagram for this scenario is constructed using a weakly nonlinear analysis beyond the point where two incommensurate temporal frequencies are excited. We further explore how epileptiform patterns can behave in the fully nonlinear regime using a bespoke numerical code for simulation of the model. The model is derived from a network of spiking neurons with chemical and electrical synapses and reduces the description of many neurons to a small number of physically meaningful macroscopic variables (population firing rate, mean membrane potential and synchrony). This allows us to identify some key physiological mechanisms underlying the susceptibility of cortical tissue to tonic-clonic seizures.

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PP1

Uncertainty Quantification for Neural Field Equations with Random Data

Neural fields equations model the activity of the brain cortex subject to an external stimulus. These spatially-extended dynamical systems are specified by modelling brain characteristics such as the synaptic kernel and firing rate of neurons, which are generally only partially available in experiments. Tools from uncertainty quantification are key to understanding neuronal behaviour and making predictions of how the brain responds to external stimuli, crucial problem in healthcare and biological applications. Motivated by these considerations, we build a numerical scheme for neural fields with random data (input, synaptic kernel, firing rate, or initial conditions) producing a pointwise approximation of the expectation and variance of neural activity at any space-time coordinate. Our approach consists in casting the system into a set of ODEs on a Banach space, and using a two steps scheme to approximate the solutions mean and variance. The implemented algorithm performs a spatial projection followed by a stochastic projection. We explain and motivate possible choices for the projectors (interpolator and orthogonal) and the corresponding quadrature rules to approximate the integrals. In particular, we demonstrate optimal convergence of stochastic collocation analytically and present numerical results.

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PP1

Bystander Effect As An Emergent Property of Individual Psychological Prospects

The bystander effect is a sociological phenomenon in which individuals are less likely to help a person in need if there are others present. Sociologists and psychologists have proposed multiple plausible reasons for the bystander effect, from ambiguity and group cohesiveness to diffusion of responsibility and mutual denial. We build a dynamical systems model based on these sociological and psychological hypotheses, along with ideas borrowed from behavioral economics; in particular, we use prospect theory to predict an individuals decision to take action or not. With this model, we find the conditions under which a bystander effect emerges from these individual decisions.

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PP1

Tracking of Buffet Oscillations in Transient Simulations of a Transonic Airfoil Using Sliding-Window Dynamic Mode Decomposition

The transonic buffet is an aircraft wing oscillation arising due to the interaction between the supersonic bubble and separation layer. A sustained buffet can damage the aircraft and as a result, it must be carefully taken into account during the aircraft design. We study the buffet that appears when the angle of attack (AoA) is increased. The onset of the buffet can be explained by Hopf bifurcation. We generated simulations for different AoA using the time-accurate Reynolds-Averaged NavierStokes solver. The described approach applies the dynamic mode decomposition (DMD) to extract flow components responsible for the buffet onset. We applied a DMD with a sliding window to track the onset of buffeting in order to adjust to non-steady-state data during the flow transient. By comparing dominant DMD mode profiles across different AoA we identify ranges of AoA values corresponding to the no oscillation, pre-buffeting, buffeting, and post-buffeting regions. We demonstrate that the described method performs well across flight conditions and airfoil shapes.

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PP1

Growth, Energy, Or Both? Different Optimization Problems for Microbial Cells

Single-celled organisms are complex dynamical systems. From just a few nutrients, they synthesize new copies of themselves by controlling thousands of chemical reactions. Their mathematical description involves large sets of ODEs describing the interconversion of metabolites by enzymes in metabolic reaction networks at steady-state. Microbial behavior can best be studied from the perspective of maximal growth rate, as this increases evolutionary fitness. This requires high reaction rates to synthesize cellular components rapidly, while the amount of catalyzing enzymes is limited. Thus, the cell faces a resource allocation problem to optimize a specific flux, which is the reaction rate per enzyme. It has been shown that specific flux is maximized by using minimal metabolic pathways called Elementary Flux Modes (EFMs) [Wortel2014]. Thermodynamics offers a different perspective on cellular growth. As observed in many physical systems, the objective here is to optimize entropy production, which is a measure for energy dissipation in the network. Here, we show when the optimization problems for specific flux and entropy production are equivalent, and how this is related to an optimal pathway length. Furthermore, we extend the mathematical formulation to realistic growth environments in the chemostat and in batch. This approach gives useful insights in the relation between different challenges a microbial cell faces and how this can be described using the theory of EFMs.

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PP1

Scalable Solution of Dynamical Systems for Modeling Tumor Growth

Computing technology is continuously making advancements that establish a framework for higher spatial resolution in mathematical modeling of time-dependent phenomena. These models are based on well-established numerical methods that become progressively more expensive with increasing spatial resolution due to the stiffness of the underlying dynamical system. To compensate, researchers must currently simplify models with assumptions, lower resolution, fewer parameter sets, etc. For certain simulations, such as the modeling of solid tumor growth, these can be compromising simplifications–results are less accurate, time intensive, and overgeneralized for individual patients. To provide doctors with accurate information for prognoses and clinical treatment decisions, greater scalability must be achieved by addressing stiffness in the dynamical system that results from spatial discretization of the full tumor growth model. Exponential Rosenbrock methods are designed for stiff problems; however, these methods rely on computing matrix function-vector products with algorithms that do not scale well. Krylov Subspace Spectral (KSS) methods frequency-dependent approach, designed to circumvent stiffness in linear problems, computes these products with greater scalability. We hypothesize that combining these two classes of methods will produce superior scalability for the solution of such dynamical systems.

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PP1

Effects of Sampling Time on Complexity-Entropy Analysis

Complexity-Entropy (CH) analysis is a tool for distinguishing chaotic and stochastic origins of time series measurements [Rosso,et.al.,Distinguishing noise from chaos, 2007], providing information on possible models for the underlying dynamics. Estimates of complexity and entropy are obtained from permutations in the time series, and are used to represent the system in the Complexity-Entropy plane (CH plane). The location of the time series provides information on the system origin. CH analysis has been applied to a wide variety of systems including fusion reactors[Zhu, et.al, Chaotic edge density fluctuations in the Alcator C-Mod tokamak, 2017], the medical field [Xiaoli, et.al, Predictability analysis of absence seizures with permutation entropy, 2007] to name a few. In this contribution, we show that continuous models should be associated with a line, rather than individual points, in the CH plane. The sampling time parametrizes the line, and the same system may show both chaotic and stochastic behavior depending on the sampling time. One direct consequence of this is that the true nature of the dynamics of the system are obscured by fine sampling time. A variety of simple models are used to illustrate this point, and a stochastic model based on a superposition of pulses, called a shot-noise process or a filtered Poisson process [Garcia, Stochastic modeling of intermittent scrape-off layer plasma fluctuations, 2012], is used in detail as a test bed.

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PP1

Flow Map Parameterization Method for Whiskered Tori in Quasi-Periodic Hamiltonian Systems

Studying invariant manifolds constitutes the center piece in understanding a dynamical system. It is a rather natural first approach —and often the only hope— to unveil the qualitative behavior of a time-evolving system. Besides the intrinsic interest of invariant manifolds, such structures have found their "real-world' analogues in celestial mechanics, astrodynamics and mission design, plasma physics, semi-classical quantum theory, magnetohydrodynamics, neuroscience, and the list goes on. In this work, we consider non-autonomous Hamiltonian systems that depend on time quasi-periodically with an arbitrary number of frequencies. Under the parameterization method paradigm, we develop theory and efficient algorithms to compute non-resonant partially hyperbolic invariant tori and their invariant manifolds using flow maps. To this end, it is essential to consider the geometrical properties of the system and of whiskered tori which results in the synergy between mathematical rigor and numerical computation. Albeit we focus on applications, we provide all the ingredients for the proofs on existence of whiskered tori and dependence on parameters using KAM techniques. For the numerical experiments, we apply our algorithms in the Elliptic Restricted Three Body Problem and compute non-resonant 3-dimensional invariant tori and their invariant manifolds keeping an eye for applications to space mission design.

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PP1

The Bifurcation Structure Within Robust Chaos of Piecewise-Linear Maps

Piecewise-linear maps arise from mathematical models in diverse applications. Families of such maps readily exhibit chaos in a robust fashion and this was popularised by Banerjee, Yorke, and Grebogi in their 1998 Phys. Rev. Lett. paper. In this poster, I will show how the family of maps they considered naturally subdivides through renormalisation, and how this concisely explains some features of the dynamics described by other researchers. I will further show how the robustness extends more broadly to orientation-reversing and non-invertible maps.

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PP1

Piecewise Holomorphic Systems

Holomorphic systems are well known in the literature due to their important properties: reversibility, integrability, non-existence of limit cycles, and complete knowledge of the phase portraits around their non-essential singularities. In this work, we are concerned about studying the piecewise holomorphic systems (PWHS). Specifically, we are interested in understanding how the trajectories of the regularized system associated with the PWHS transit through the region of regularization. In addition, we know that holomorphic systems have no limit cycles, but piecewise holomorphic systems do, so we provide conditions to ensure the existence of limit cycles of these systems. Additional conditions are provided to guarantee the stability and uniqueness of such limit cycles.

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PP1

A New Framework for Harnessing Reactivity

In modeling Earth systems and other applications, an important recurring question is whether those systems maintain healthy regimes not just at dynamic attractors but also during transient excursions away from those attractors. For ODE models, these excursions are not due only to nonlinearities; they can also occur in the linearization. Since transient excursions in linearized systems are not preserved by diagonalization, we develop a new framework for analyzing linear systems through the lens of reactivity (the maximum instantaneous rate of radial amplification). We shift attention to a radial and tangential decomposition of the vector field and conjugate by rotation to generate equivalent matrices that preserve reactivity. In particular, we use our new framework to pick four equivalent matrices that give more direct access to reactivity and highlight interesting parallels between reactivity and eigenvectors.

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PP1

Utility Functions for Predator-Prey Game: A Possible Connection Between Esox Lucius-Gobio Gobio Model and Utility Functions

A generalization of the utility functions to predator-prey population is defined, considering that the utility functions depend on various parameters that suitably describe animal instincts, considering both physical and environmental conditions. Both running or being quiet have been considered as possible strategies for each person. Our study shows that the most important cooperative strategiesboth animals running or staying quiet be considered as Nash equilibrium solutions to suitably define the game. Lastly, we propose a mathematical model to describe the interacting behavior of predator and prey and we discuss the possible connection between the Esox Lucius-Gobio Gobio model and utility functions.

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PP1

Dynamics of a Piecewise-Linear Second-Order Delay Differential Equation

We study the dynamics of a piecewise-linear second-order delay differential equation that is representative of feedback systems with relays (switches). In particular, our model describes a single-input single-output system in which the delayed feedback is a bandpass filtered relay signal with a constant delay. The system under study exhibits strong multi-rhythmicity, the coexistence of many stable periodic solutions for the same values of the parameters. We present a detailed study of these periodic solutions and their bifurcations. Starting from an integro-differential model, we show how to reduce the system to a set of finite-dimensional maps. We then demonstrate that the parameter regions of existence of periodic solutions can be understood in terms of border-collision bifurcations, which correspond to transitions between maps, and that the stability is determined by smooth bifurcations.

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PP1

Localized Structures with Heterogeneous Tails

We are interested in localized structures with heterogeneous tails, that arise as solutions to nonlinear partial differential equations with spatially varying coefficients. Such solutions include (travelling) pulses and fronts that have heterogeneous tails. Nonlinear PDEs with spatially varying coefficients emerge from application based models, such as ecology models, where the spatially varying coefficients represent a varying vegetation terrain. In this case, the corresponding pulse solution can be interpreted as a (possibly moving) vegetation patch. For various reaction-diffusion systems with spatially varying parameters, we construct these localized structures by finding heteroclinic and homoclinic orbits of the corresponding ODE system. After the construction of such localized structures, we investigate their stability, supplemented by numerical results and compared to the stability of the solutions where the parameters are constant in space. Furthermore, we numerically investigate the interaction between concatenated (front and back) solutions and the stability of these new solutions.

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PP1

Data-Driven Phase Reduction with Memory

Phase reduction is a well-established model reduction technique for limit cycle oscillators, and phase models have been fruitfully used to gain insights into the dynamics of forced and networked oscillators. However, standard phase reduction methods are valid only when contraction to the limit cycle is sufficiently strong. It is well known, for example, that forced oscillators can exhibit chaos, whereas phase oscillators can never be chaotic. Here, we report on a study of data-driven non-Markovian phase models that are designed to capture the response of limit cycle oscillators to stochastic forcing. Our guiding principles are time-invariance and a property we call the zero forcing principle, which states that the reduced model must be consistent with the (trivial) time evolution of phase variables. We assess our approach on prototypical examples of limit cycle oscillators.

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PP1

A Passing Star in the Hyperbolic Restricted Three-Body Problem and Earth's Climate

It is known as Milankovitch cycles that Earth's long-term climate cycle matches with combination of Earths eccentricity, obliquity, and precession. However, due to the chaotic behavior of the solar system, Olsen et al (2019) showed that there are mismatches between the celestial computation and the geological climate data beyond 60 million years ago. Chandramouli (2020) speculated that the geologic data might be able to detect the effect of a passing star. Chandramouli applied the planar hyperbolic restricted three-body problem (HR3BP) to the Sun, a rogue star, and Jupiter. In our study, we extend Chandramoulis planar problem to motions in space. When approximating the effect of perturbation made by a passing star, we use both standard numerical methods and machine learning. We expect to show if a star passes close enough to the solar system could be reflected in the Earths geological record.

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PP1

Using Phase-Amplitude Reduction and the Infinitesimal Shape Response Curve to Study Coupled Oscillators

Phase reduction is a promising technique to study the synchronization of both coupled deterministic and stochastic oscillators. However, in certain cases, such as strong coupling or large Floquet multipliers, phase-reduction methods can fail to provide an accurate approximation of the dynamics. The use of isostable (amplitude) coordinates may be introduced to augment the phase description, providing a more complete representation of system behavior. Phase-amplitude coordinates allow for the study of both the timing and shape of system oscillations. A complementary approach in the deterministic case is the infinitesimal shape response curve (iSRC), a variational method that characterizes the shape and timing response of limit-cycle dynamics under sustained perturbation. However, the relation between phase-amplitude coordinates and the iSRC has not been previously considered. Here, we show that the iSRC admits a simple representation in phase-amplitude coordinates, and we relate the phase and amplitude response curves to the iSRC. We demonstrate the utility of the iSRC by showing how it may be used to track the average and extrema of specific system observables. We verify our theory by applying the iSRC to biologically motivated case studies.

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PP1

Data-Driven Methods for Control of a Nonlinear Ball-on-a-Wheel System

Data-driven control methods are applied to a nonlinear Ball-on-a-Wheel system, where a ball is balanced on a driven wheel. The presented control strategies stabilize this unstable stationary point of the system. In addition, the data-based output matching problem is solved, where a given reference trajectory is tracked. For the data-based controller design, a trajectory-based approach as well as an approach based on the Koopman operator are used. The necessary data could be obtained from a laboratory experiment or model simulations, where the equations of motion are derived using the Lagrange formalism. Finally, the numerical results obtained by the two data-based approaches and a model-based control are discussed and compared with a laboratory experiment.

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PP1

Geometric Blow-Up for Folded Limit Cycle Manifolds in Three Time-Scale Systems

Geometric singular perturbation theory provides a powerful mathematical framework for the analysis of 'stationary' multiple time-scale systems possessing a critical manifold, particularly when combined with a method of desingularization known as blow-up. The theory for 'oscillatory' multiple time-scale systems which possess a limit cycle manifold instead of a critical manifold is less developed, especially in the non-normally hyperbolic regime. In this poster presentation we show how the blow-up method can be applied to analyse the global oscillatory transition near a regular folded limit cycle manifold in a class of three time-scale systems with two small parameters. The systems considered behave like oscillatory systems as the smallest perturbation parameter tends to zero, and stationary systems as both perturbation parameters tend to zero. The additional time-scale structure is crucial for the applicability of the blow-up method, which cannot be applied directly to the two time-scale counterpart of the problem. Our methods allow us to describe the asymptotics and strong contractivity of all solutions which traverse a neighbourhood of the global singularity. Our results cover a range of different cases with respect to the relative time-scale of the angular dynamics and the parameter drift. The poster presentation is based on the preprint [Jelbart et al., Geometric Blow-up for Folded Limit Cycle Manifolds in Three Time-Scale Systems, arXiv:2208.01361]

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PP1

Controlling Complex Networks with Complex Networks: the Herding Control Problem

Herding is a collective behaviour emerging in those situations where a group of agents start to behave collectively in the same way. Examples include people in a crowd starting moving in the same direction or investors buying the same stocks. In this talk, we discuss the herding control problem where a group of agents (the herders) need to control the collective dynamics of another group of agents (the targets). Differently from the problem of controlling a complex network by acting on a fraction of its nodes, here control of a complex network of target agents is achieved by controlling the dynamics of a complex networks of herders interacting with them. In this talk, we solve the problem of herding a group of stochastic target agents towards a desired region in the plane by orchestrating the collective behaviour of a group of cooperating herders with limited sensing. We design the herders as a network of coupled oscillators whose dynamics is adapted in a distributed manner to that of the targets. We split the herding task in a set of hierarchical actions that the herders can perform on different time scales. We can then adjust the time scale separation so as to achieve the final goal. We investigate the emerging collective behaviour of herders and targets, the effectiveness of the proposed control strategy and the scaling laws linking the time separation of the actions, the number of agents, and the initial configurations of herders and targets.

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PP1

Creating Data-Driven Model Discovery Framework with Applications in Traffic Modeling

Autonomous and connected vehicles are expected to transform the automotive industry in the future. For these vehicles to be able to share roads with humans, they must understand how humans interact with surrounding vehicles. The existing traffic models rely on strong assumptions and are not scalable or generalizable. Driving in traffic involves constantly gathering and responding to information from the environment and surrounding vehicles. Consequently, interaction can be viewed as the relationship between stimuli and responses. To gain a deeper understanding of interaction, we will identify which stimuli and to what extent influence driving in different situations and thus determine the interaction network by conducting an information-theoretic (IT) analysis. An approach to discovering traffic models based on data-driven complex systems modeling will be presented here. Using IT measures, we will identify a library of candidate variables for modeling directly from data, rather than relying on assumptions. Next, we will discover interpretable and parsimonious models with the fewest linear combinations of nonlinear functions from a library of candidate variables that describe the driving process with no prior speculation. To accomplish this, we will use the SINDy framework, which uses sparse regression, is robust to noisy data, to determine and validate the functional relationships between the candidate variables, thus building traffic models.

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PP1

Early Warning Signals of Bifurcations - The Case of $\alpha-$stable Noise

Noisy dynamical systems approaching a bifurcation may show changes in their statistical properties, most notably an increase in variance and autocorrelation. Such so called early warning signals can also be observed in some observational or experimental datasets before a regime change, making them an interesting tool for forecasting loss of stability in real-world applications. The theory behind this phenomenon is so far only well described for Gaussian noise. In this case one can obtain an Ornstein-Uhlenbeck process through linearization, for which then analytical solutions of variance and autocorrelation in dependence of the bifurcation parameter exist. However, many real-world data streams are not normally distributed but can for example exhibit heavy tails, thus violating the assumption of the classical theory. We here study early warning signals in systems driven by α-stable (Lvy) noise, a natural extension which entails Gaussian noise as well as a broad class of heavy-tailed distributions. We discuss conditions for existence of classical early warning signals (variance and autocorrelation) in such systems and implications for simulations and practical applications. In cases where classical early warning signs cannot be applied, we propose alternative metrics better suited to forecast bifurcations in systems driven by α-stable noise.

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PP1

Selection of Dynamically Distinct Spatiotemporal Patterns in a Mean-Field Model for Neuronal Activity

In this work, we use numerical simulations and bifurcation theory techniques to study the emergence of stable spatiotemporal patterns in a mean-field model for neuronal activity. We identify sufficient conditions on the models parameters for the generation of traveling waves (TWs), standing waves (SWs), and modulated waves (MWs). We show how the relative contribution of the intrinsic cell dynamics, the network structure, and certain features of a feedback connectivity loop (slow vs fast and weak vs strong, negative feedback component) lead to the selection of TW, SW, and MW spatiotemporal patterns.

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PP1

A Mini-Review of Developmental Mechanisms to Complexify Dynamical Systems

Alan Turing not only pioneered morphogenesis, but in a little-known 1948 paper, he also investigated connectionist ideas, proposing that several "unorganized' machines would then be organized by some sort of "genetical search' [Turing, Intelligent Machines, 1948]. Turing thus was the first to propose *Evolutionary Artificial Neural Networks* (EANN), though they only became more popular in the nineties. While morphogenesis can explain aspects of embryonic development, Turing did not propose nor investigate developmental aspects for his connectionist architectures. In 1997, Sipper *et al.* proposed the POE framework, which distinguishes three broad levels of organization in bio-inspired systems: evolution (phylogeny), developmental processes (ontogeny), and learning (epigenesis) [Sipper *et al.*, A Phylogenetic, Ontogenetic, and Epigenetic View of Bio-Inspired Hardware Systems, 1997]. While evolutionary algorithms and learning are frequently combined, considering developmental mechanisms in dynamical systems remains rare. Yet, we argue that such biologically-inspired complexification mechanisms are key for lifelong adaptation and learning, allowing computational resources to grow with the model's needs as it operates. In this piece, we review work that uses generative, developmental, or other growth mechanisms to gradually increase the size and complexity of dynamical systems.

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PP1

Deep Learning for Chaos Detection

One of the main topics in dynamical systems is the detection of chaotic regions in the parameter space. To locate these regions, classical techniques as Lyapunov Exponents can be used [R. Barrio, S. Serrano. A Three-Parametric Study of the Lorenz Model. Physica D, 2007]. However, recently some authors have proposed to use new methods as Deep Learning [N. Boull, V. Dallas, Y. Nakatsukasa, D. Samaddar. Classification of Chaotic Time Series with Deep Learning. Physica D, 2020]. In this poster, we provide the results obtained when Deep Learning is used to perform the chaos detection task in a dynamical system. Moreover, we compare these results with those obtained with Lyapunov Exponents [R. Barrio, . Lozano, A. Mayora-Cebollero, C. Mayora-Cebollero, A. Miguel, A. Ortega, S. Serrano, R. Vigara. Deep Learning for Chaos Detection. Preprint, 2023].

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PP1

A Dynamics-Inspired Model for Phonation-

Induced Aerosolization

Human phonation induces the formation and ejection of aerosols from the mouth. In infectious speakers, phonation-induced aerosolization can facilitate the transmission of airborne viruses. However, the formation of such aerosols is challenging to study 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 gain insight into these complicated dynamics, we have developed a computational framework that models the ejection, motion, and subsequent breakup of sessile liquid originating on the surface of the vocal folds. Much like Robert Shaw's classic dripping faucet system, droplets ejecting from a vibrating elastic surface can be modeled as a damped simple harmonic oscillator with nonlinear springs and dampers in which mass is ejected with each oscillation. The framework proposed here combines a droplet-ejection model that is based on a Rayleigh-Taylor instability with a model of nonlinear vibrational elastodynamics induced by fluid-structure interaction between exhaled air and the vocal fold tissues. Its output yields a spray distribution that we can compare to experimental aerosol size distributions collected during laryngeal phonation.

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PP1

Polynomial Mixing Rates in Non-Monotonic Alternating Shear Flows

Polynomial mixing rates are typical in laminar mixing systems with slow moving fluid near boundaries. Here we present other mechanisms for a slower than exponential mixing rate, illustrated by a variety of non-monotonic alternating shear maps on the torus. In particular we show that a fundamental piecewise linear model exhibits 'ghost boundaries around which mixing is slowed, which are not a result of physical boundary conditions but arise naturally in the dynamics. For this system we establish asymptotic (strong, measure-theoretic) mixing properties and derive rigorous bounds on mixing rates using results from the chaotic billiards literature. Smoothing the shear profiles provides a further mechanism for slowed mixing and significantly complicates the analysis. We first explore smooth perturbations to the piecewise linear examples, highlighting the key impact smooth non-monotonicity has on mixing quality and the challenges it poses to establishing rigorous results. Based on this analysis, protocols to maximise chaotic mixing are derived with relevance to microfluidic mixing devices.

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PP1

Global Synchronization of Nonlinear and Non-Diffusively Coupled Oscillators

The emergence of a synchronous behavior of coupled dynamical systems is widely observed in many biological and engineered networks and is essential to understand their mechanism and control them. A plethora of work is done to find conditions that foster synchronization in diffusively coupled systems, in which the coupling vanishes on the synchronization manifold. However, there are few analytical approaches to understanding synchronization behavior in non-diffusively coupled networks. Motivated by neuronal models connected through chemical synapses, we investigate sufficient conditions for non-diffusively coupled oscillators to synchronize globally. Our global stability method follows an analytical contraction-based approach that explicitly relates synchronization to systems' intrinsic dynamics, coupling dynamics, and the underlying network topology. We compare this method to a local or linear stability approach called the master stability function, a numerical method that provides necessary and sufficient conditions for network synchronization.

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PP1

3D Lagrangian Coherent Structures and Relative Dispersion in Oceanic Subduction

Vertical oceanic transport is responsible for the exchange of biogeochemical and geophysical properties between the surface ocean and the interior. Therefore, knowledge of the dynamics of this process is highly desired in fields of study such as marine biology and physical oceanography. It is hypothesized that on the submesoscale there exist coherent pathways responsible for the transport of subducted water parcels and supporting evidence shows the existence of water mass in the stratified pycnocline that originated from the mixed layer. We aim to assess the primary direction of dispersion of water parcels subducted from the surface using data from the Process Study Ocean Model (PSOM). In our approach, we compute the Finite-Time Lyapunov Exponent (FTLE) field in 2D and 3D and reveal Lagrangian Coherent Structure (LCS) candidates in the flow domain. We then compute the left and right singular vectors of the flow map gradient to assess the dominant dispersion direction of subducted water parcels. Examination of the cross-sections of the FTLE fields reveal LCS candidates that indicate the location of the downwelling front. The left and right singular vectors indicate primary horizontal separation along the downwelling front but after a scaling of the z-components is employed, the left and right singular vectors indicate strong vertical separation along the front.

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PP1

Pattern Formation in Mechanochemical Models

In biology, self-organization and pattern formation happen on many different scales. For example in embryonic development, a homogeneous clump of cells evolves into a complex organism. Alan Turing described this process with a system of reaction-diffusion equations of two chemicals: a short range activator and a long range inhibitor [A. M. Turing, The Chemical Basis of Morphogenesis, Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 237(641):37-72, 1952]. He found that spatially inhomogeneous perturbations result in a periodic pattern close to the homogeneous equilibrium. In our research, we include mechanical cues as well as chemical cues, since they also play an important role in tissue deformation [C.M. Nelson et al., Emergent patterns of growth controlled by multicellular form and mechanics. PNAS, 102(33):11594-9, 2005.]. The so-called mechanochemical model describes the deformation of a surface depending on a diffusing morphogen [M. Mercker et al., Modeling and computing of deformation dynamics of inhomogeneous biological surfaces, SIAM Journal of Applied Mathematics, 73(5):17681792, 2015]. Here, the curvature of the membrane takes on the role of the inhibitor. We study the possible patterns in this model by inspecting the steady state phase space using tools like numerical simulation and Geometric Singular Perturbation Theory. With this approach, we get a better analytical understanding of a wide range of possible patterns.

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PP1

Tardys Quantifiers: Extracting Temporal And Reversible Dynamical Symmetries in Complex Systems

One of the great challenges in complex and chaotic dynamics is to reveal the details of its underlying determinism. This can be manifest in the form of temporal correlations or structured patterns in the dynamics of a measurable variable. These temporal dynamical structures are sometimes a consequence of hidden global symmetries. Here we identify the temporal (approximate) symmetries of a semiconductor laser with external optical feedback, based on which we define the Temporal And Reversible DYnamical Symmetry (TARDYS) quantifiers to evaluate the relevance of specific temporal correlations in a time series. We show that these symmetries are also present in other complex dynamical systems, letting us to extrapolate one system's symmetries to characterize and distinguish chaotic regimes in other dynamical systems. These symmetries, natural of the dynamics of the laser with feedback, can also be used as indicators in forecasting regular-to-chaos transitions in mathematical iterative maps. We envision that this can be a useful tool in experimental data, as it can extract key features of the deterministic laws that govern the dynamics of a system, despite the lack of knowledge of those specific quantitative descriptions.

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PP1

Numerical and Theoritical Study of Patterns in a Chemotaxis Model

Models of biological interactions are in full swing. They come in different flavors, one of them being systems of partial differential equations, which are then studied by mathematicians. Here, we will be interested in the establishment of stationary solutions to problems of the form $\partial_t U = \Delta(\Phi(U)) + f(U)$, with a computer-assisted method. Starting from a known approximate solution, we get back to study a fixed point problem to solve our initial problem. This fixed point then becomes our existing and unique theoretical solution in a neighbourhood of our approximate solution. The difficulty lies in the choices we make when reducing the problem. In particular, the non-linearity of the equations is a significant obstacle. More precisely we will look at a chemotaxis model where $\begin{cases} \partial_t u &= \Delta(\gamma(v)u) + \sigma u(1-u) \\ \partial_t v &= \varepsilon\Delta v + u - v \end{cases}$. In this type of model the search for patterns and the study of their stability is interesting, which justifies our numerical to theoretical approach. We will look at different results according to the chosen function γ : rational fraction, decreasing exponential, power series, ...

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PP1

Mixed Mode Oscillations and Mixed Mode Bursting Oscillations in Two Three-Timescale Neuronal Systems

We are concerned with two types of complex oscillatory dynamics frequently perceived in multiple-timescale dynamical systems - mixed mode oscillations (MMOs) and mixed mode bursting oscillations (MMBOs). Both terms are used to describe the alternation of small-amplitude oscillations (SAOs) and large-amplitude oscillations or bursting oscillations. It is well known that SAOs during the silent phase arise either from canard dynamics associated with folded singularities or a slow passage through a delayed Andronov-Hopf bifurcation (DHB) of the fast subsystem. In this work, two neuronal systems involving three timescales are considered. We establish the conditions under which the two separate mechanisms in the two-timescale setting, canard and DHB, can interact in the three-timescale context to produce more robust MMOs or MMBOs. Specifically, we explain the dynamic mechanisms underlying MMOs in a coupled Morris-Lecar system and study MMBOs in a cortical theta oscillator model. Our analysis also demonstrates that a third timescale is required in the theta oscillator to produce MMBOs, suggesting that MMBOs studied here represent three-timescale phenomena.

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PP1

Constructive Methods in Kam Theory for Quasi-Periodic Hamiltonian Systems with Application to Tokamaks

In this poster, we present the parameterization method in a-posteriori format to prove a KAM theorem for Lagrangian tori in quasi-periodic Hamiltonian systems. This approach consists of finding a parameterization for a torus satisfying an invariance equation that depends on dynamic and geometric properties. We derive explicit error estimates for the parameterization of an approximately invariant torus. The proof shows the convergence of a quasi-Newton iterative scheme, taking advantage of the geometric structure of the problem to simplify the functional equations that are solved in each iterative step. The theorem states that if the invariance error is sufficiently small and non-degeneracy conditions are satisfied, there exists a parameterization of a true invariant torus. The schemes derived from the proof can be converted into efficient and reliable numerical methods for the computation of invariant tori. We have applied the theorem to a Tokamak model, where a torus confines plasma via magnetic field lines. We compute an invariant torus that functions as a barrier between two chaotic regions. This is joint work with Renato Calleja and Alex Haro.

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PP1

Chaotic Diffusion in Delay Systems

We consider systems that show chaotic diffusion and are characterized by a delayed reaction. A modulation of the delay time has immense consequences for the diffusive character of the system. Varying continuously the modulation amplitude or the mean delay time leads to wild fluctuations of the diffusion constant by orders of magnitude. Counterintuitively, an enhancement of diffusion is accompanied by a strong reduction of the effective dimensionality of the system, which is a consequence of sweeping through various distinct types of chaotic diffusion. It will be explained, how such effects can be understood in terms of simple dynamical systems theory. Our results are relevant for a large class of systems, where finite propagation speeds are relevant and some feedback mechanism is changing with time.

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PP1

Understanding Oscillations in a Model of Intracellular Calcium Dynamics

Mathematical models of intracellular calcium dynamics are known to exhibit a wide variety of complex oscillations, some of the complexity occurring because of the existence of different time scales in the model and some because the time-scale structure itself can differ in different regions of phase space. In this project, a mathematical model of calcium dynamics in hepatocytes is investigated. This system has at least two time scales, and can exhibit two distinct types of oscillation, which we call narrow spikes and broad spikes. We are interested in understanding the mathematical and physiological mechanisms underlying the observed broad spike oscillations. We use a combination of geometric singular perturbation theory and numerical bifurcation analysis to explain the origin and nature of the broad spike oscillations.

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PP1

A Component-Wise Multistep Method for Stiff Systems of ODEs

Established time-stepping methods have difficulty with stiff systems of ODEs that contain coupled components that vary at vastly different rates. Explicit methods require a very small time step to obtain an accurate solution, while implicit methods require the solution of ill-conditioned systems of linear equations, increasing computational expense. To overcome stiffness, an alternative is a component-wise approach that approximates the exponential for each component of the solution in some basis individually, such as Krylov subspace spectral (KSS) methods. KSS methods are component-wise, explicit, high-order one-step methods for systems of ODEs obtained from PDEs, with stability characteristic of implicit methods. Unlike other time-stepping approaches, KSS methods compute each Fourier coefficient of the solution from an individualized approximation of the solution operator of the system of ODEs. As a result, KSS methods scale effectively to higher spatial resolution. This poster will present the design and analysis of explicit and implicit multistep formulations of KSS methods to provide a “best-of-both-worlds” situation that combines the efficiency of multistep methods with the stability and scalability of KSS methods. The effectiveness of component-wise multistep methods will be demonstrated using numerical experiments. It will also be shown that the region of absolute stability exhibits striking behavior that helps explain the scalability of these new methods.

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PP1

Low Dimensional Representations of the Ergodic Quotient

The analysis of a dynamical systems ergodic sets is useful in understanding how the phase space decomposes into invariant sets. The ergodic quotient is a structure that simplifies such analysis. Instead of dealing with the potentially complicated shape of ergodic sets themselves, the ergodic quotient represents them as points in a vector space. This can be done by averaging a basis of functions along the systems trajectories, and viewing these averages as coordinates for points that uniquely represent the original sets. This collection of points is the aforementioned ergodic quotient. Different bases used in this averaging lead to different representations of the quotient, thereby giving different insights into the ergodic sets themselves. The trade-off in studying this quotient, as opposed to the original whole sets, is that it necessarily lies in an infinite dimensional space due to the manner it is represented. It is therefore useful to perform dimensionality reduction and manifold learning, to embed the quotient into a more accessible, lower dimensional space. This work studies different choices for function bases and manifold learning techniques that could be used, tied with an analysis of the numerical setbacks used in the creation and reduction of the ergodic quotient. In particular, this work focuses on wavelet bases, tied with a survey of various manifold learning/embedding algorithms.

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PP1

Modifications to Chemical Reaction Networks and Their Dynamical Consequences

A chemical reaction network consists of a set of species, complexes, and reactions. From these networks, a system of ordinary differential equations with mass action kinetics can be derived, and a number of important dynamical properties stem directly from properties of the network. One important network property is the networks deficiency, a non-negative integer index of the networks complexity. We relate how deficiency changes in relation to a family of operations known to preserve dynamical properties such as multistationarity and periodic orbits. We can thus derive further conditions where these network modifications preserve another important dynamical quantity called Absolute Concentration Robustness, which gives a strong condition of invariance to initial conditions under the appropriate parameters.

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PP1

Dynamics of Intermittent Synchrony of Ping Gamma Rhythms

Synchronization of neural activity in the gamma frequency band is associated with various cognitive phenomena. The present study explores how synaptic properties in pyramidal-interneuronal circuits affect the fine temporal patterning of neural synchrony, that is the variability of the neural synchronization on very short timescales. If two signals show only moderate synchrony strength, it may be possible to consider these dynamics as transitions between synchronized and desynchronized states. This patterning of the synchronized dynamics may be independent of the average synchronization strength. We use models of connected circuits expressing pyramidal-interneuronal gamma (PING) activity to explore the temporal patterning of synchronized and desynchronized episodes. We show how the changes in the synaptic strength alter the temporal patterning of synchronized dynamics (even if the average synchrony strength is not changed). We also show that circuits with different patterning of synchronization in time may have different sensitivity to synaptic input. The synaptic changes, which affect gamma oscillations and result in different properties of information processing in the brain (and its abnormalities in several neurological and neuropsychiatric disorders), may mediate physiological properties of neural circuits not only via change in the average synchrony level, but also via change of how synchrony is patterned in time over very short time scales.

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PP1

Effects of Group-Individual Interaction in a Generalized Voter Model with Hyperedge Opinions

The study of opinion dynamics provides useful insights into the large-scale trends in opinion formation and acts as a platform for rich dynamical behavior. When individuals participate in group interactions there may be a tendency for the group to come to some level of agreement, forming a group opinion. Here we consider a hypergraph generalization of a non-linear voter model where nodes and hyperedges each have opinions drawn from a binary set. In our model, nodal opinions are updated probabilistically via a response function which depends on the average neighbor opinion and all hyperedge opinions which the node participates in. Hyperedge opinions are updated similarly based on all participating nodes and their own opinion. This model produces both group-individual agreement and opposition as stable behavior. Furthermore, the model contains regions with short term network cascades and stable oscillations. The formation of these oscillations is tied to a decrease in the correlation between pairwise and hyperedge degrees. Recently there has been much interest in extending dynamical processes on pairwise networks to hypergraphs and to search for novel dynamical behavior. The oscillations induced by nodal hyperdegree correlations observed in our model are a clear example of how hyperedges can fundamentally change the dynamics observed in the corresponding pairwise network models.

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PP1

Homoclinic Orbits Near the Hamiltonian-Hopf Bifurcation in the Suspension Bridge Equation

Homoclinic orbits for the suspension bridge equation $u'' + \beta u' + e^u - 1 = 0$ have been proven to exist for all parameter values $\beta \in (0, 1.9]$. We want to complete the picture by proving these orbits for $\beta \in [1.9, 2)$. This is the most challenging parameter range since we are approaching the Hamiltonian-Hopf bifurcation point, where the homoclinic orbit disappears. Our approach is to combine computer assisted proof techniques with rescaling methods to achieve such goal.

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PP1

Multiplexed Synaptic Plasticity in Biological Neural Networks

Networks of (biological) neurons are subject to constant change, with the impact any given neuron exerts on any other varying according to numerous factors. This has long presented a puzzle for neuroscientists: How does such plasticity impact function? While researchers consider many versions of this question, one major focus concerns reward-seeking behavior generated by so-called three-factor plasticity rules (equations describing synapse change). This type of plasticity is fundamental, both biologically and because of connections with mathematical theories of learning and control. How it interacts with other sorts of plasticity, particularly those not informed by feedback from the external world, is poorly understood however. The matter is important, because joint actions of plasticity likely support the powerful learning observed in animals. Previously, weve shown how the geometry of plasticity in neural networks relates to memory retention and generalization. Here, we expand on those analyses, examining algorithmic biases induced by performance-non-contingent plasticity. Each such form of plasticity induces dynamics in the space of network functions, and their interactions control ultimate function. We analyze the resulting geometries, flows, and fixed points of these rules to understand the functional properties of multiplexing them.

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PP1

Network Hysteresis: A Framework for Understanding Emergent Oscillations

Oscillatory systems are ubiquitous in neuroscience, governing locomotion, breath, circadian rhythms, and many more essential biological functions. The mechanisms of rhythmogenesis in such systems are well understood when one or more components of the system are endogenously oscillatory, but often no rhythmogenic core can be identified. Analysis of the mechanism of operation in such cases is challenging. We propose the concept of network hysteresis as a general model of oscillation in emergent oscillations. Nonlinear oscillatory behavior is frequently characterized by hysteresis, where one subsystem is bistable for intermediate values of a slow variable. On each bound of the intermediate range, one of the two attractors becomes unstable. Hysteresis can generate oscillations when the slow variable reciprocally drives the full system towards loss of stability. Hysteresis is known to occur in neuron models, but has not been investigated in emergent oscillations. We present a conceptual model of these emergent oscillations and compare it to a biologically plausible network model of a swim CPG in sea slugs.

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PP1

Deep Learning the Dynamical Model for Evolution of Persistent Homology of Two Dimensional Vortex Dynamics

Developing nonlinear models for high-dimensional time-evolving data is difficult and computational analysis of such models is additionally expensive. An example of such data is the time-varying persistence homology description of the topology of a set of vortices evolving under the joint velocity field.This study builds on data-driven modeling techniques from the literature that use deep-learning to first reduce the data dimension, and then build a nonlinear ODE whose evolution matches the data. The first step is accomplished using an autoencoder, a neural network which is capable of reducing and expanding dimensions. Autoencoder obtains lower-dimensional manifold coordinates of input data. The second step is accomplished using neural ordinary differential equations. This produces a neural network acting as the ordinary differential equation describing the time evolution on this reduced dimension manifold.We validate and demonstrate this approach on data generated using several well-studied dynamical systems. Then, we apply this approach to develop a model for the evolution of persistent homology descriptors of two-dimensional vortex-dominated fluid flows.

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PP1

Input-Response Relations for Traveling Waves in Neural Fields with Synaptic Depression

Traveling waves in spatially-extended dynamical systems can be perturbed far from equilibrium due to persistent inputs and heterogeneities. Here, we study the emergence of traveling waves in a neural field model, an integro-differential equation whose kernel describes connectivity between neurons, and with activity-dependent dynamic weakening of connectivity. Combined excitatory connectivity and its dynamic weakening can lead to marginally stable traveling fronts (with attenuated backs) or pulses of a fixed speed. Transient stimuli temporarily displace and deform waves as characterized by a wave response function. In the limit of weak perturbations, we can derive a hierarchy of equations that describe the deformation and displacement of the traveling wave in powers of a small parameter. At linear order, we leverage a solvability and boundedness condition that takes the form of the Fredholm Alternative to asymptotically approximate the wave response function. We can also invert the problem to determine for a given target pulse speed, different from the natural speed, a biologically-realistic stimulus that will produce a nearby traveling wave with the perturbed speed.

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PP1

Mathematical Modeling of Clonal Expansion Before the Onset of Disease Via a General Population Study

The myeloproliferative neoplasms (MPNs) are a group of blood cancers marked by over-production of one or more types of blood cells, which can lead to thrombosis and other complications. MPNs develop slowly and are driven by mutations in the hematopoietic stem cells (HSCs). Their slow development (years to decades) affords a unique opportunity to study their onset, but until recently little data has been available from individuals not yet showing overt disease. Thanks to the ambitious Danish General Suburban Population Study (GESUS) conducted in suburban Zealand, Denmark, we have identified a cohort of individuals with one of the main driver mutations for MPN (namely JAK2V617F) and have obtained follow-up measurements of their allele burden spanning over 10 years. We show that these data are consistent with a Moran model governing the competition between healthy and mutated HSCs, and estimate the selective advantage of the mutant clone for each individual. Notably, we find that for many individuals, the change in allele burden over many years is statistically consistent with zero selective advantage. This contrasts with prior studies that have focused on patients with active MPN disease, in whom the mutant cells are generally found to outcompete the healthy cells. Our results have possible implications for our understanding of the very early phases of MPN disease, in particular the mechanisms underlying acquisition and expansion of JAK2-mutant stem cells.

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PP1

Optimizing Reward Rate on Forced-Choice Tasks

The tradeoff between speed and accuracy is a fundamental feature of decision-making. Two-alternative forced-choice tasks, in which an agent chooses between two actions and receives a probabilistic reward, afford a powerful experimental paradigm for investigating this tradeoff. Here we describe an optimal-observer model for a two-alternative forced-choice task with learning, implemented as a drift diffusion model (DDM). This model assumes that the agent optimizes reward rate on the task. Previous work has typically operationalized reward rate as $E[R]/E[T]$, that is, the expected reward divided by expected time per trial. In general, however, this is not equal to the true expected reward rate $E[R/T]$. We derive an expression for $E[R/T]$ and analyze the differences between it and the traditional formula, investigating where $E[R]/E[T]$ serves as a valid approximation to $E[R/T]$ and where the approximation breaks down.

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PP1

On Chaotic Non-Stationary Steady-States and Biological Processes

A late-1,970s contribution by Dr. K.-D. Willamowski and Dr. Otto Rssler related to a chemical reaction arrangement that is feasible able to sustain a chaotic type of non-stationary motion is examined. The arrangement of the chemical-reaction network transforms 3 distinct species into 2 distinct species, utilizing 3 transient intermediate species; the concentrations of these 3 intermediate species are the aspects of this arrangement that are able to access this sustained chaotic type of presence. There exist 2 primary objectives with this undertaking: 1) continue developing numerical tools for the analysis of more elaborate collections of non-linear differential-equations, particularly as they relate to reaction networks and 2) lay-out an initial argument for why chaotic-and-beyond type of non-stationary steady-states are not compatible with the type of motion that underlies biological activity.

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PP1

Equity-Based Optimization of Vaccination Strategies for COVID-19

There are significant disparities in COVID-19 infection, hospitalization, and death rates between different racial or ethnic groups. To study this inequity, we construct a mathematical model of COVID-19 that is stratified by both age and race. We consider two racial groups: non-Hispanic white persons and persons belonging to minority groups (including non-Hispanic black persons, non-Hispanic Asian persons, non-Hispanic American Indian or Alaska Native persons, and Hispanic or Latino persons). We first fit our model to data from Oregon at the beginning of 2021, before vaccines were available. Next, we optimize the allocation of a limited amount of vaccine among the age and racial groups using objective functions which minimize either the number of deaths, the inequity in deaths between racial groups, or the combination of both over the time period of a few months. Inequity is measured in terms of differences in mortality rates between races summed across age groups. We found that to minimize the number of deaths, the older age groups in both racial groups should be vaccinated first, as well as some portion of the group with the most contacts. To minimize inequity, vaccine was first allocated to the minority population in the young-adult and middle-aged groups. When minimizing both deaths and inequity, the optimal vaccination strategy was more complicated, achieving significant reduction in inequity while preserving the majority of the reduction in mortality.

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PP1

Patterns of Chaotic Switching in Superradiance and Counter-lasing

Superradiance is an effect in which a tightly confined group of atoms can emit light in a quantum-mechanically enhanced fashion. It has been experimentally observed in a variety of platforms from Bose-Einstein condensates to nitrogen-vacancy centers in diamond. In physics, the emergence of superradiance is an example of a dissipative quantum phase transition. In the so-called semiclassical limit, the emergence of superradiance can be described as a pitchfork bifurcation of a set of nonlinear ordinary differential equations. On the other hand, counter-lasing is an effect whereby optical systems achieve lasing that is seeded by dissipation rather than an injection of energy. We show that in a system where these two effects are in competition, a chaotic attractor possessing a mirror symmetry emerges which exhibits interesting switching behavior between symmetry-related regions of phase space. With a symbolic dynamics approach, we identify global bifurcations corresponding to connections between saddle objects in phase space which determine the organization of different switching patterns.

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PP1

Synchronization and Random Attractors for Reaction Jump Processes

This work explores a synchronization-like phenomenon induced by common noise for continuous-time Markov jump processes given by chemical reaction networks. A corresponding random dynamical system is formulated in a two-step procedure, at first for the states of the embedded discrete-time Markov chain and then for the augmented Markov chain including also random jump times. We uncover a time shifted synchronization in the sense that – after some initial waiting time – one trajectory exactly replicates another one with a certain time delay. Whether or not such a synchronization behavior occurs depends on the combination of the initial states. We prove this partial time-shifted synchronization for the special setting of a birth-death process by analyzing the corresponding two-point motion of the embedded Markov chain and determine the structure of the associated random attractor. In this context, we also provide general results on existence and form of random attractors for discrete-time, discrete-space random dynamical systems.

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PP1

Extinction Dynamics of Cascade Food Webs

Ecologists use a variety of synthetic food web networks (cascade, niche, generalized cascade, etc.) to predict key structural properties of complex food webs. These synthetic food webs are inherently unstable in the sense that incorporating dynamics, even deterministic dynamics, causes many species to go extinct. We consider the cascade food web with competitive Lotka-Volterra dynamics and investigate the effect of initial conditions, birth and death rates, species interaction rates, and predation efficiency on the extinction dynamics. We also derive analytical results for food chains, which are used to gain insight into the persistence of cascade food webs.

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PP1

Multidimensional Stability of Planar Traveling Waves for Stochastically Perturbed Reaction-Diffusion Systems

We consider reaction-diffusion equations that are stochastically forced by a small multiplicative noise term that is white in time, colored in space, and invariant under translations. Formally, we have $\partial_t u = \Delta u + f(u) + \sigma g(u)\dot{W}_t$, where $u \in \mathbb{R}^n$, $n \geq 1$, and $(x,t) \in \mathbb{R}^d \times \mathbb{R}_+$, $d \geq 2$. The translational invariance property of the noise W_t is a natural assumption to pose, which is inspired by applications. An example of non-linearities f and g that fits into our framework are $f(u) = u(1-u)(u-a)$ with $a \in (0,1)$ and $g(u) = u(1-u)$. In this setting, we stochastically force the parameter a, i.e., we replace a in the deterministic PDE ($\sigma = 0$) by $a + \sigma\dot{W}_t$. The multidimensional stability of planar traveling waves for the deterministic setting has been studied by many, see for instance T. Kapitula (1997), *Multidimensional Stability of Planar Travelling Waves*. Existence and stability of wave profiles for $\sigma > 0$ and $d = 1$ is established, by means of a phase tracking method, in C.H.S. Hamster, H.J. Hupkes (2020), *Traveling Waves for Reaction-Diffusion Equations Forced by Translation Invariant Noise*. Inspired by these works, we set up a phase tracking framework for $d \geq 2$. In particular, we show how these stochastically perturbed reaction-diffusion systems above can be understood as SPDEs, where the noise is a cylindrical Q-Wiener process.

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PP1

Nonlinear Feedback Linearization with Physics-Informed Neural Networks

In this work, we present a physics-informed machine learning (PIML) scheme for the feedback linearization with pole placement in one step of nonlinear complex systems. We assess the performance of the method using (a) a benchmark nonlinear discrete map for which the feedback linearization law can be derived analytically, thus containing very steep gradients resembling singularity at the boundaries, and (b) a microscopic Monte Carlo simulation of CO oxidation on a catalytic lattice; in the later case we couple the proposed methodology with the Equation-free framework. We show that the proposed PIML scheme outperforms in terms of numerical approximation accuracy the established numerical implementation that in such cases involves the expansion of the feedback law as power series and the construction and solution of a system of homological equations with respect to the coefficients of the series, especially in regimes with steep gradients.

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PP1

The Effect of Neuromodulation on Respiratory Bursting Neurons

Respiration is an involuntary process in all living beings required for our survival. The preBötzinger complex (preBötC) in the mammalian brainstem is a neuronal network that drives inspiratory rhythmogenesis, whose activity is constantly modulated by numerous neuromodulators through altering properties of the network. In this work, we will combine experimental results and dynamical systems modeling to examine the effect of Norepinephrine (NE), an excitatory neuromodulator, on respiratory dynamics via a focus on preBötC. We use bifurcation analysis to uncover the mechanisms by which NE modulates preBötC bursting neurons, as well as how it interacts with other neuromodulation to affect respiratory dynamics. Our analysis also explains how NE can induce intrinsic pacemaker properties in active non-pacemakers.

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PP1

Existence and Persistence of Steady States for Dynamical Systems on Large Networks

In this paper we study steady state solutions for dynamical systems on networks. These types of dynamical systems occur in reaction-diffusion models, coupled oscillators, Lotka–Volterra systems, and elsewhere. For large networks we employ the concept of a graph limit, called a graphon. The graphon can be used to define a non-local dynamical system on the unit interval. Identifying a steady

state solution for the non-local equation allows us to prove that, for finite networks sufficiently close to the graphon in an appropriate norm, the solution persists as an equilibrium for the dynamical system on the finite graph.

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PP1

Bifurcation Studies in Families of Piecewise-Linear Nontwist Maps

Families of piecewise linear versions of the area-preserving standard nontwist map [D. del Castillo, J.M. Greene and P.J. Morrison, Physica D91, 1 (1996)] and of some of its generalizations are considered. Phase space structures that can suppress or enable global transport (e.g., bifurcations including periodic orbit collisions and separatrix reconnections) are analyzed and computed.

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PP1

Non-Linear Stability of Triangular Equilibrium Points in Non-Resonance Case with Perturbations

The present study deals with the normalization of Hamiltonian for the non-linear stability analysis in non-resonance case of the triangular equilibrium points in the perturbed restricted three body problem with perturbation factors as radiation pressure due to first oblate-radiating primary, albedo from second oblate primary, oblateness and a disc. The problem is formulated with these perturbations and Hamiltonian of the problem is normalized up to fourth order by Lie transform technique consequently a Birkhoff's normal form of the Hamiltonian is obtained. The Arnold-Moser theorem is verified for the non-linear stability test of the triangular equilibrium points in non-resonance case with the assumed perturbations. It is found that in the presence of radiation pressure, stability range expanded, significantly with respect to the classical range of stability however, because of albedo, oblateness and the disc, it contracted gradually. Moreover, it is observed that alike to the classical problem, in the perturbed problem under the impact of the assumed perturbations, there always exist one or more values of the mass ratio μ within the stability range at which discriminant $D_4 = 0$, which means the triangular equilibrium points are unstable in non-linear sense. Thus, it is concluded that presence of perturbations in the problem disturb not only the non-linear stability property but also the stability range.

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PP1

Scaling Relations for Auxin Waves

The vasculature of plants is thought to be initiated through the formation of polarized transport channels for the phytohormone auxin. The formation of these auxin transport channels has been hypothesized to occur through a positive feedback of the auxin onto the polarization of auxin transporters, including PIN1, in the plant cell [Merks, Canalization without flux sensors: a traveling-wave hypothesis, 2007]. The 'up-the-gradient' model [Jnsson, An auxin-driven polarized transport model for phyllotaxis, 2006], which assumes that auxin is transported to neighboring cells with the highest auxin concentration, can explain the formation of these auxin transport channels. Here, we formally analyze this model [Bakker, Scaling Relations for Auxin Waves, 2022]. We show that this model admits a family of travelling wave solutions that is parameterized by the height of the auxin-pulse. We uncover scaling relations for the speed and width of these waves and verify these rigorous results with numerical computations. In addition, we provide explicit expressions for the leading-order wave profiles, which allows the influence of the biological parameters in the problem to be readily identified. Our proofs are based on a generalization of the scaling principle developed by Friesecke and Pego to construct pulse solutions to the classic Fermi-Pasta-Ulam-Tsingou model, which describes a one-dimensional chain of coupled nonlinear springs.

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