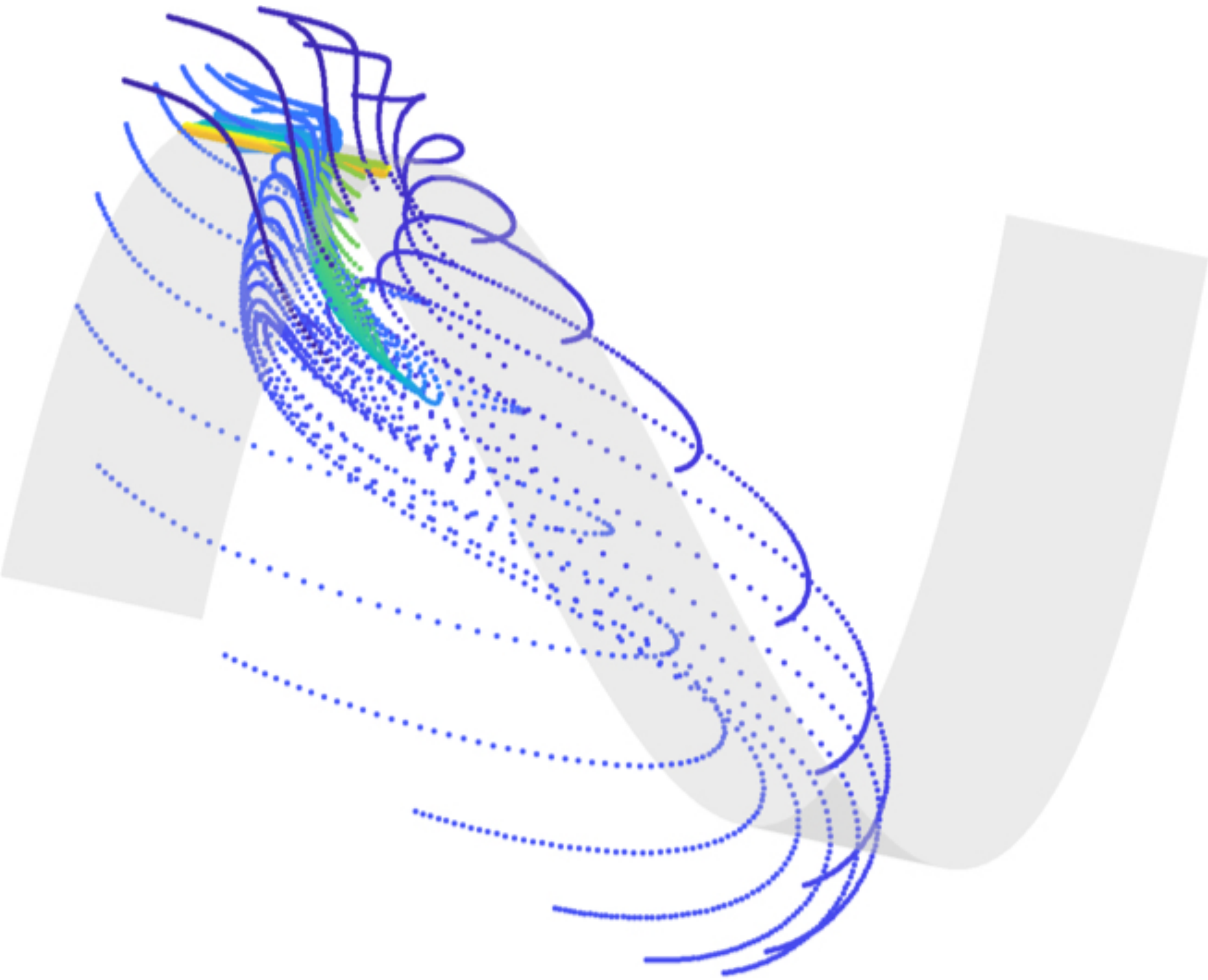
Dynamicsdays 2021



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Intrinsic Rhythms in a Giant Single-Celled Organism and the Interplay with Time-Dependent Drive, Explored via Self-Organized Macroscopic Waves

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Living Systems often seem to follow, in addition to external constraints and interactions, an intrinsic predictive model of the world — a defining trait of *Anticipatory Systems*.

Caulerpa is a marine green alga with differentiated organs resembling leaves, stems and roots; while an individual can exceed a meter in size, it is a single multinucleated giant cell. Active transport has been hypothesized to play a key role in development. Yet, the most recent reports studying organelle transport in *Caulerpa* are over three decades old.

Using Raspberry-Pi cameras, we track over weeks the morphogenesis of tens of samples concurrently, while tracing at minute resolution the variation of green coverage; the latter is attributed to chloroplasts redistribution at whole-organism scale, and reveals a pulse-like behavior. Our observations indicate that the initiation of these waves, in regenerating algal segments cultured under periodic illumination, precedes the external light change. The temporal spectrum shows a circadian period, which persists over days even under constant illumination.

We explore the system under non-circadian periods, its relaxation times — analogous to jet lag recovery, and the limits at which the system no longer follows the period of the external drive.

The role of mild and asymptomatic infections on COVID-19 vaccines performance: a modeling study

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With approximately 96 COVID-19 vaccines at various stages of clinical development, there are currently four vaccines authorized for emergency use in Europe. Different vaccine efficacies are reported, with remarkable effectiveness against severe disease. However, the so called sterilizing immunity, occurring when vaccinated individuals cannot transmit the virus, is yet to be confirmed. With an uneven roll out of vaccination, we investigate, using mathematical models, the impact of asymptomatic/mild COVID-19 infections on vaccine performance.

In this paper, results obtained for two vaccination models, the vaccine V1 protecting against severe disease, and the vaccine V2, protecting against disease and infection, are compared to a model without vaccination, evaluating the reduction of hospitalizations in a population. The different COVID-19 vaccines currently in use have features placing them closer to one or the other of these two extreme cases, V1 and V2, and insights on the importance of asymptomatic infection in a vaccinated population are of a major importance for the future planning of vaccination programme.

Our study shows that vaccines protecting against severe disease but failing to block transmission might not be able to reduce significantly the severe disease burden under low or intermediate vaccine coverage. While in the case of asymptomatic or mild disease cases accounting for most of the transmission, the non-sterilizing vaccines are eventually increasing the number of overall infections in a population. Here, the effects of COVID-19 vaccination in different epidemiological scenarios of coverage and efficacy are evaluated, giving insights on how to best combine their use and optimize the reduction of hospitalizations.

Low regularity integrators for the Gross-Pitaevskii equation

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In this presentation I will introduce a novel time discretization for the Gross-Pitaevskii equation at low-regularity with non-smooth potential. The local error analysis will be given, as well as global error estimates when equipped with periodic boundary conditions or set on the full space. We establish these error estimates at low regularity by using discrete Strichartz and Bourgain type estimates. We will also provide higher order extensions, following new techniques based on decorated trees series analysis inspired by singular SPDEs. These new schemes, together with their optimal local error, allow for convergence under lower regularity assumptions than required by classical methods. Indeed, while different discretization techniques for dispersive equations, such as discretizing the variation of constants formula (e.g. exponential integrators) or splitting the full equation into a series of simpler subproblems (e.g. splitting methods), have been established in the past, these classical schemes often break-down at low regularity. Recently, a unifying low regularity time discretization framework was introduced to treat parabolic, hyperbolic, dispersive as well as mixed equations. However, an important class of equations is missing, namely equations with a potential (or noise). To close this gap we propose a novel low-regularity integrator to a prototypical NLS equation with a non-smooth potential.

Game Theory of Developmental Processes

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Developmental processes are dynamic and complex, and can be viewed from the perspective of interacting agents. We will provide a means to understand developmental agency at multiple organizational scales through the notion of ontogenetic agency, which will in turn enable an approach called developmental game theory. We will begin by reviewing the notion of an ontogenetic agent and how this construct relates to the formation of strategies. In short, ontogenetic agents taking the form of cells, morphogens, gene products, engage in a developmental process and produce coherent states. The interactions between these states (in the forms of competition or cooperation) can be characterized in a game model. While these strategies rely upon natural features such as developmental constraints and trade-offs rather than requiring a conventional decision-making apparatus, it does not preclude ontogenetic agents from engaging in autonomous and collective behaviors. A series of game-theoretic models suited to select problems in development will then be reviewed. These include different classes of game used to model different aspects of development: 0-player, single-player, n-player, and combinatorial. We will then discuss the broader dynamics of these games, such as equilibria, computational complexity, and evolutionary games. In addition to toy examples, these models will then be extended to systems, evolutionary equilibria, and homeostatic/allostatic regulation. In conclusion, we will consider how developmental game theory models provide a means to better understand the phenomena of cellular and biological decision-making.

Network morphology to store memories

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Simple organisms manage to thrive in complex environments. Remembering information about the environment is key to take decisions. Physarum polycephalum excels as a giant unicellular eukaryote being even able to solve optimisation problems despite the lack of a nervous system. Here, we follow experimentally the organism's response to a nutrient source and find that memory about nutrient location is encoded in the morphology of the network-shaped organism. Our theoretical predictions in line with our observations unveil the mechanism behind memory encoding and demonstrate the P. polycephalum's ability to read out previously stored information. Our theoretical investigation in the memory formation ability of adaptive networks in general reveals that the erosion of weak network links is key to store information about the past.

Phase-sensitive tipping: How cyclic ecosystems respond to contemporary climate

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R.C. Tyson and S. Wieczorek

We identify the phase of a cycle as a new critical factor for tipping points in cyclic systems subject to time-varying external conditions. As an example, we consider how contemporary climate variability induces tipping from a predator-prey cycle to extinction in a paradigmatic predator-prey model with an Allee effect. Our analysis of this model uncovers a counter-intuitive behaviour, which we call phase-sensitive tipping or (P-tipping), where tipping to extinction occurs only from certain phases of the cycle. To explain this behaviour, we combine global dynamics with set theory and introduce the concept of partial basin instability for limit cycles. This concept provides a general framework to analyse and identify sufficient criteria for the occurrence of phase-sensitive tipping in externally forced systems.

Chimeras and fractals from two populations of quadratic maps

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Chimera states have high cross-disciplinary impact since they show rich and complex dynamics generated by a simple network structure [1]. Abrams et al. [2] argued that two populations of coupled time-continuous phase oscillators are the simplest system that supports chimera states. We here consider an even simpler system, namely two populations of coupled time-discrete quadratic maps [3]. We demonstrate that this system shows not only a plentitude of symmetric dynamics but also a variety of symmetry broken chimera states. The symmetry can be broken with regard to the synchronization and/or periodicity of individual populations. All patterns arise spontaneously from random initial conditions, i.e. there is no need to craft initial conditions to induce them. Moreover, our system allows us to generate intriguing fractal structures in the complex plane of the control parameter of the quadratic map.

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[2] D. Abrams, R. Mirollo, S. Strogatz, and D. Wiley. Solvable model for chimera states of coupled oscillators. Phys. Rev. Lett. 101, 084103 (2008).
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Impact of the range of the interactions and time delays on synchronization patterns

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Traditionally, the updating of the constituent units is made synchronously (parallel updating), however, the elements in real arrays do not react in perfect synchrony. Then, the inclusion of time delays or other kinds of asynchronicity seems more realistic and leads to quite different emerging patterns. In the spatial domain, a realistic ingredient in modeling extended systems is the coupling range. We investigate the formation of completely synchronized states (CSSs) in CMLs as a function of interaction strength, range of the interaction (that can vary from first neighbors to global coupling), and a parameter that allows one to scan continuously from non-delayed to one-time delayed dynamics. We identify in parameter space, periodic orbits, limit cycles, and chaotic trajectories, and describe how these structures change with delay. These features can be explained by studying the bifurcation diagrams of a two-dimensional non-delayed map, allowing us to understand the effects of one-time delays on CSSs, e.g., regularization of chaotic orbits and synchronization of short-range coupled maps, observed when the dynamics is moderately delayed.

Stability of filters for deterministic dynamics

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The Bayesian formulation of the data assimilation problem leads to the problem of non-linear filtering. In many applications, the dynamical models are deterministic and chaotic, in which case most of the classical stability results for nonlinear filtering are not applicable because such systems do not satisfy the assumption of controllability. In this talk, we discuss our recent results (doi:10.1016/j.sysconle.2020.104676 and arxiv:1910.14348) proving asymptotic filter stability for deterministic, chaotic dynamics. We will discuss the relation between the dynamical characteristics of such systems and the asymptotic filtering distribution, as well as the implications for data assimilation problems in earth sciences.

Bifurcation analysis of oscillatory combustion using hydrodynamic simulation

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The oscillatory combustion can be observed in a bundle of candles. Such oscillatory combustion occurs when the number of bundled candles is greater than a threshold value. The amplitude and frequency of the oscillation also depend on the number of candles. However, it is difficult to experimentally determine the bifurcation structure regarding this oscillation since the number of candles is discrete. In this study, therefore we reproduced the oscillatory combustion by the hydrodynamic simulation and analyzed the bifurcation structure. We performed the two-dimensional hydrodynamic simulation, assuming that the gas around the flame is compressible Newtonian fluid. We adopted the flame sheet model, in which we assumed that the reaction rate is sufficiently fast in combustion and that the Lewis number, the ratio between the thermal diffusion coefficient and the mass diffusion coefficient, is unity. By adopting this model, we only need to solve the three equations: the Navier-Stokes equation, the equation of continuity, and the advection-diffusion equation. By the numerical simulation, we could reproduce the oscillatory combustion for appropriate conditions. Parameter dependences of the amplitude and frequency were qualitatively consistent with the experimental results. By varying parameters continuously, we found that an oscillatory state appeared through a subcritical Hopf bifurcation. A rising vortex pair, which should correspond to a vortex ring in a three-dimensional system, was found only in the oscillatory state. Such a rising vortex ring will provide insight for the mechanism of the oscillatory combustion.

Phase defects in electrical patterns during heart rhythm disorders

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The heart is a dynamical self-regulating system in which complex patterns of electrical activation are formed during cardiac arrhythmias. These patterns often result into waves rotating around their core, named vortices or rotors. The conventional mathematical framework assumes that rotors rotate around a single point, called a phase singularity, near the rotor center. However, during clinical observations extended lines of conduction blocks are seen in the elongated rotor core. Here, we present a novel mathematical description where the activation wave circles around a phase defect line (PDL) in 2D or a phase defect surface (PDS) in 3D. These phase defect structurs are similar to branch cuts in complex analysis. We demonstrate PDL existence in numerics and experiment and present topological considerations on the occurring structures.

Superfluid swimmers

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The propulsion of living microorganisms ultimately relies on viscous drag for body-fluid interactions. The self-locomotion in superfluids such as He 4 is deemed impossible due to the apparent lack of viscous resistance. Here, we investigate the self-propulsion of a Janus (two-face) light-absorbing particle suspended in superfluid helium He 4 (He-II). The particle is energized by the heat flux due to the absorption of light from an external source. We show that a quantum mechanical propulsion force originates due to the transformation of the superfluid to a normal fluid on the heated particle face. The theoretical analysis is supported by the numerical solution of the Ginzburg-Landau-Khalatnikov model for a superfluid. Our results shed light on the dynamics of inclusions in a superfluid and stimulate experiments.

Experimental observations in a turbulent BEC: characterization and universal scaling properties

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One of the out-of-equilibrium states of great interest in superfluids is the state of turbulence. In this state, the proliferation of vortices or waves, creates one of several known states of turbulence. From equilibrium, with energy injection, there is evolution establishing a cascade of energy that causes migration of energy to high moments, resulting in a dependence of power law type in the energy spectrum. The reason the system evolves this way has to do with its quest for equilibrium, reaching possibly a stationary state. If the energy injection is ceased, the system evolves in time. Observing the high moment component in the distribution allows us to verify its dependence by determining whether it is a non-thermal state. We detected in our experiment regions of excitation, where exponential (rather than Gaussian) dependence reveals the presence of non-thermalizing states. Such out-of-equilibrium states exhibit universal behavior when scaled. This universal behavior is of great interest, especially if associated with turbulent states. (Financial support from FAPESP, CNPq and CAPES. This work had the participation of A. Garcia, G. Telles, L. Machado, S. Couto, L. Madeira, G. Roati, P.Castilho, P. Tavares, A. Cedrin and G. Roati)

Projective and Telescopic Projective Integration for Kinetic Mixtures

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We propose fully explicit projective integration schemes for non-linear collisional kinetic equations for mixtures. The methods employ a sequence of small forward-Euler steps, intercalated with extrapolation steps. The telescopic approach repeats said extrapolations as the basis for an even larger step. This hierarchy renders the computational complexity of the method essentially independent of the stiffness of the problem, which permits the efficient solution of equations in the hyperbolic scaling with very small Knudsen numbers. We validate the scheme against standard test cases, and we demonstrate its prowess in dealing with large mass ratios and other complex phenomena. This is joint work with T. Rey.

Towards quantum turbulence in exciton-polariton condensates

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Exciton-polaritons are hybrid particles formed by the strong coupling of excitons and photons in semiconductor heterostructures, typically in optical microcavities. Exciton-polaritons inherit from the photonic component a light mass and long temporal coherence, while significant particle-particle interactions originate from their excitonic component. In the last two decades, exciton-polariton condensation and superfluidity have been demonstrated up to room temperature, as well as the presence of solitons and quantized vortices and half-vortices, emerging as a promising platform for the study of quantum fluids in an optical environment [1, 2, 3]. Here, we show our recent results aiming to the all-optical control and trapping of a quantum fluid of exciton-polaritons. By tracking on a picosecond time-scale a large number of quantized vortices, we present the first experimental attempts to explore turbulent regimes in two-dimensional exciton-polariton condensates.

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Delay dynamics in an excitable micropillar laser with saturable absorber

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Micropillar lasers with saturable absorber have been shown to display a fast excitable behavior and several neuromimetic properties such as refractory period, spike latency and temporal summation. They are thus interesting building blocks for neuro-inspired photonic processing. When self-coupled with delayed feedback, they can act as a working memory with specific short and long terms behaviors. In the short term, they can regenerate any temporal spike pattern, thus realizing an optical buffer memory. In the long term, we show that the only stable regimes are limit cycle oscillations : any information stored initially in the temporal spike pattern is lost. However, we show that this realizes a content addressable memory which computes and can retrieve information from an imperfect input. We discuss the experimental results in parallel with a numerical model which yields excellent agreement. We also highlight a novel bifurcation in this system giving rise to pulse timing symmetry breaking: irregularly spaced, periodic spiking patterns can be stable in specific parameter regions and controlled by the feedback time, thus enriching the spike patterns that can be produced by this kind of optical source.

Mechanochemical pattern formation in cells

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The cortex is a thin network of filamentous proteins lying on the inner face of the cell membrane, which crucially contributes to controlling cell shape. It exhibits a rich spatiotemporal dynamics, which emerges from chemical and mechanical contributions. A major chemical contribution comes from signaling cascades, which are initiated by cell's environmental stimuli, while a major mechanical contribution comes from molecular motors, which cross-link cortical filaments and produce local active stresses. In their interpretation of cortical dynamics, cell biologists often assume that chemistry governs mechanics, for instance by recruiting cortical components or by activating molecular motors, without being affected by it. However, there is evidence that mechanics feeds back into chemistry, for instance through molecular motors that produce cortical active flows able to spatially redistribute signaling molecules. The cortical dynamics resulting from such mechanochemical coupling is largely unexplored. We theoretically investigate it by developing a minimally complex hydrodynamic model that accounts for experimentally relevant couplings between cortex and signaling. We find that mechanics and chemistry reinforce each other's nonlinear dynamics, producing patterns of purely mechanochemical origin that qualitatively differ from those produced in absence of mechanochemical coupling. Overall, the rich dynamics predicted by our model suggests that cells could leverage mechanochemical feedbacks to attain specific self-organized states without having to rely uniquely on signaling cascades.

Adaptive Bayesian Inference of Markov Transition Rates

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Many complex phenomena involve stochastic transitions between environmental, conformational, or population-level states. To model the dynamics of such systems, researchers have often turned to Markov chain models; e.g., for population dynamics, viral epidemics, etc. However, when fitting these models, it can be helpful to identify the most efficient methods for data collection to most efficiently specify transition rate parameters. In this talk, we propose an adaptive algorithm to infer the transition rates of a Markov process from time series data from sequential samples of the state. Leveraging Bayesian inference, we construct a stochastic optimization problem that finds the optimal successive sampling times. This produces a posterior distribution over the transition rates with minimal variance. We then apply our method to classic Markov chain models, including the birth-death process and a periodic biased random walk, to demonstrate its effectiveness. Our results will provide practical tools to experimentalists and modelers studying complex stochastic behavior and will aid in the design in more efficient experimental design.

The mechanics of finite-time blowup in an Euler flow

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One of the most fundamental issues in fluid dynamics is whether or not an initially smooth fluid flow can evolve over time to arrive at a singularity – a state for which the classical equations of fluid mechanics break down and the flow field no longer makes physical sense. While proof remains an open question, numerical evidence strongly suggests that a singularity arises at the boundary of a flow like that found in a stirred cup of tea. The goal of this talk is to explain, from a fluid-mechanics perspective, why.

Behaviour of self-organised, large-scale vegetation patterns

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As a response to climatic changes, many ecosystems self-organize into large-scale spatial patterns - for example, vegetation bands or patches emerging in the process of desertification. In mathematical models (singularly perturbed reaction-diffusion equations with parameters that may vary in time and space) these patterns present themselves as interacting localized structures (e.g. pulses). In this talk, I explain how the dynamics of these can be analyzed via (geometric singular) perturbation theory and numerical simulations. I will describe how their response to further environmental change is a combination of slow (migratory) pattern rearrangement (on a N-dimensional manifold M_N) and fast pattern-to-pattern transitions (from one manifold M_N to another M_M, with $M < N$). This leads to a framework of interlinked phase portraits that describes the location (and possible annihilation) of the localized structures over time. Using this framework, I will indicate the effect ground topography can have on movement and stability of vegetation patterns. Furthermore, I will also highlight the differences between small and large pattern transitions and describe the dependency on the rate of climatic change: slow change leads to sporadic, large transitions, whereas fast change causes a rapid sequence of smaller transitions.

Observation of vortex dynamics in a fluid of light

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Fluids of light merge many-body physics and nonlinear optics, revealing quantum hydrodynamic features of light when it propagates in nonlinear media. One of the most outstanding evidence of light behaving as an interacting fluid is its ability to carry itself as a superfluid. Using an all-optical experimental platform, based on a biased photorefractive crystal, we have recently reported a direct experimental detection of the transition to superfluidity in the flow of a fluid of light past an (weakly perturbing) obstacle. Here, considering a stronger and larger obstacle, we investigate the dynamics of the resulting turbulent flow of light. We observe, as the Mach number increases, the generation, evolution and merging of pairs of vortices of opposite circulation, eventually leading to the generation of a dark solitons through an instability process. Moreover, we also consider a line of obstacles with a varying separation. When the obstacles are quite far away from each other, we show that they act as independent, generating independent pairs of vortices. As soon as they get close enough (separation of the order of the size of the obstacle), vortices begin to interact, annihilate, and eventually lead to a snake instability.

Emergence of solitary states in adaptive nonlocal oscillator networks

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Partial synchronization patterns have become an important paradigm in complex network science over the last decade. Just recently, a new phenomenon, called solitary state, in the transition from incoherence to complete coherence was discovered. We analyze a nonlocally coupled ring network of adaptively coupled phase oscillators and observe a variety of frequency-synchronized states including solitary states. Despite the fact that solitary states have been observed in a plethora of dynamical systems, the mechanisms behind their emergence were largely unaddressed in the literature. Here, we show how solitary states emerge due to the adaptive feature of the network. By using numerical and analytical methods, we explore the spectral properties of solitary states and classify several bifurcation scenarios in which these states are created and stabilized.

How bacterial swimmers with multiple run modes navigate chemical gradients

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Bacterial chemotaxis is one of the most fundamental examples of directional navigation in the living world. It is key to many biological processes, including the spreading of bacterial infections and the formation of biofilms. While Escherichia coli, the well-known paradigm of bacterial chemotaxis, only swims as a pusher, it was recently reported that many other bacterial species exhibit several distinct swimming modes—the flagella may, for example, pull the cell body or wrap around it. How do the different run modes shape the chemotaxis strategy of a multimode swimmer? Here, we investigate chemotactic motion of the soil bacterium Pseudomonas putida as an example of a multimode swimmer. By simultaneously tracking the position of the cell body and the configuration of its flagella, we demonstrate that individual run modes show different chemotactic responses in nutrition gradients and, thus, constitute distinct behavioral states. On the basis of an active particle model, we demonstrate that switching between multiple run states that differ in their speed and responsiveness may provide the basis for robust and efficient chemotaxis in complex natural habitats.

Curious dynamics of a golf ball bounce

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The bounce of a ball in sports such as tennis, cricket or football has been studied extensively with many experimental data available to support the analysis. The common denominator for these models is an impact of a compliant ball off a rigid ground. A bounce of a golf ball is a very different problem though, where the analysis focuses on the impact of a rigid body off a compliant surface. Previous studies of this problem have been largely limited by the lack of experimental data.

In our talk we present our approaches at modelling the bounce of a golf ball where we try to match the physical intuition with experimental data. We extend previous work by creating large experimental campaigns. In the modelling we carefully distinguish the slipping and rolling (sliding) scenarios and we approach the problem with a wide spectrum of initial conditions in mind. We show that the obtained data is well correlated using linear models, though divergent from the classical coefficient of restitution approaches. We present a bifurcation analysis of piecewise-smooth Filippov systems leading us to conclusion that the bouncing golf ball can undergo a grazing-sliding or switching-sliding bifurcations. In the last part of this talk we will focus on the methods which we are developing for fitting data into such non-smooth systems.

Interactions and Noninteractions: Synchrony and beyond in oscillators with dead zones

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Whether or not oscillators interact, may depend on their state. Here we formalize the concept of a dead zone as an open set in state space where the interaction vanishes. Moreover, we elucidate how dead zones shape the collective network dynamics of synchronization and beyond.

Stochastic time-delayed models of autoimmunity

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One significant contribution to onset and development of autoimmunity comes from infections. In this talk, I will discuss a mathematical model of immune response to a viral infection, and subsequent onset of autoimmunity, with account for different types of T cells and their interactions, as mediated by cytokines. In many respects, immune system is a multi-factorial stochastic system, with many processes taking place over non-negligible time scales. To account for this, special attention will be paid in the model to the role of stochasticity and time delays. I will present the results of the analysis of stochastic oscillations around deterministically stable states, as well as the effects of stochasticity on the dynamics of the system in a bi-stable regime. I will show how variance of stochastic fluctuations and their coherence depend on system parameters and time delays. I will discuss a method for deriving stochastic delayed differential equations and a corresponding numerical simulation algorithm [1], and will show how it can be used to simulate stochastic dynamics in a time-delayed model of autoimmunity [2].

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Controlling the shape of clusters with a macroscopic field

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Macroscopic forces produced by electric fields or thermal gradients are often used to displace single objects, but also clusters of atoms [1], molecules [2], or colloids [3]. In addition, they have the ability to alter the shape of the clusters. This effect is well known for example in the case of electromigration, where complex shapes emerge from instabilities and from the coupling of the electric field direction and the cluster edge anisotropy [4]. In this work, we present a model to control the shape of clusters undergoing thermal fluctuations with the temporal variations of a macroscopic field. We find the optimal policy for tuning the external force to reach a target cluster configuration in minimum time. We reformulate this problem as a Markov Decision Process for the optimization of first passage times on a graph, and solve the associated Bellman equation using Dynamic Programming. We exemplify this strategy with two-dimensional clusters subject to a macroscopic force that can be switched along a fixed direction. We find that targets can be reached even if they are a priori not compatible with the symmetry of the force. For small clusters, we find that the optimal choice for the external field exhibits a discrete set of transitions as the temperature is varied. In addition, this optimal policy is not unique and exhibits degeneracies that originate either from the obvious symmetries of the target state or from hidden symmetries of the dynamics. Finally, there is an optimal temperature at which the target configuration can be reached in minimum time.

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Using machine-learning modeling to understand macroscopic dynamics in a system of coupled maps

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Machine-learning techniques not only offer efficient tools for modeling dynamical systems from data, but can also be employed as frontline investigative instruments for studying the underlying physics: we explore this possibility by studying macroscopic motion emerging from a system of globally coupled maps, which are known to exhibit non trivial collective behaviours. We build a coarse-grained Markov process for the macroscopic dynamics both with a machine-learning approach and with a direct numerical computation of the transition probabilities; then we compare the outcomes of the two analyses. After testing the ability of the stochastic machine-learning approach to describe the collective dynamics, we show how this technique yields insight into the physics itself. By modulating the input available to the network, we infer important information about the effective dimension of the attractor, the persistence of memory effects, and the multiscale structure of the dynamics.

Patient-Specific Simulation of Potentially Pre-Arrhythmogenic Substrate in Embolic Stroke of Undetermined Source

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Cardiac magnetic resonance imaging (MRI) has revealed fibrotic remodeling in embolic stroke of undetermined source (ESUS) patients comparable to levels seen in atrial fibrillation (AFib). Our group has recently used computational modeling to understand the absence of arrhythmia in ESUS despite the presence of putatively pro-arrhythmic fibrosis. We have reconstructed MRI-based atrial models 45 ESUS patients, alongside a control set of 45 models reconstructed from MRI scans of AFib patients. The fibrotic substrate's arrhythmogenic capacity in each of these 90 patient-specific models was assessed computationally using a virtual overdrive pacing protocol. Reentrant drivers (i.e., self-sustaining "rotor" patterns of bioelectric excitation) were induced in 24/45 (53%) ESUS and 22/45 (49%) AFib models. Models in which rotors were induced had more fibrosis ($16.7 \pm 5.45\%$) than non-inducible models ($11.07 \pm 3.61\%$; $P < 0.0001$); however, inducible subsets of ESUS and AFib models had similar fibrosis levels ($P = 0.90$), meaning the intrinsic pro-arrhythmic substrate properties of fibrosis in ESUS and AFib are essentially indistinguishable. This suggests some ESUS patients have latent pre-clinical fibrotic substrate that could be a future source of arrhythmogenicity. Thus, our work prompts the novel hypothesis that ESUS patients with fibrotic atria are spared from AFib due predominantly to an absence of arrhythmia triggers.

Detection of Local Mixing in Time-Series Data Using Permutation Entropy

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While it is tempting in experimental practice to seek as high a data rate as possible, oversampling can become an issue if one takes measurements too densely. These effects can take many forms, some of which are easy to detect: e.g., when the data sequence contains multiple copies of the same measured value. In other situations, as when there is mixing—in the measurement apparatus and/or the system itself—oversampling effects can be harder to detect. We propose a novel, model-free technique to detect local mixing in time series using an information-theoretic technique called permutation entropy. By varying the temporal resolution of the calculation and analyzing the patterns in the results, we can determine whether the data are mixed locally, and on what scale. This can be used by practitioners to choose appropriate lower bounds on scales at which to measure or report data. After validating this technique on

several synthetic examples, we demonstrate its effectiveness on data from a chemistry experiment, methane records from Mauna Loa, and an Antarctic ice core.

Penrose superradiance in photon fluids

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Superradiance is the amplification of waves scattered by a rapidly rotating object, first proposed in 1969 by Roger Penrose [1] who predicted this effect near rotating black holes. However, measuring such astrophysical amplification is still technologically challenging. In this context, analogue gravity studies have attracted major attention due to their versatility in proposing laboratory tests of otherwise inaccessible phenomena [2]. In this way, the concept of superradiance has been extended to other physical systems and recently measured in water waves in a draining bathtub experiment [3]. Here we show that superradiance occurs also in nonlinear optical systems, especially in a 2D rotating nonlinear superfluid. By the excitation of Bogoliubov modes in the photon fluid [4], we quantify the amount of anomalous scattered positive modes outside the ergoregion, i.e. that region, analogue to that of rotating black holes, where a body cannot be at rest as seen by an asymptotic observer. We verify the proposed analysis by a pump-probe experiment. Creating an analogue black hole with a pump super-Gaussian vortex beam with angular momentum (OAM) l in a nonlinear, defocusing medium, we test the scattering of a coaxial weak Gaussian probe with OAM m loosely focused onto the pump core. Our results show that superradiated modes can be observed in a photon fluid experiment and open new perspectives in understanding the superradiance scattering.

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Structure vs dynamics: controlling chemical communication in arrays of diffusively coupled micro-oscillators via compartimentalization properties

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Networks of diffusively coupled inorganic oscillators, confined in nano- and micro-compartments, represent a powerful tool for studying collective behaviours observed in biological systems. By taking advantage of a microfluidic technique, we study the dynamics of arrays of diffusively-coupled Belousov-Zhabotinsky (BZ) oscillators encapsulated in water-in-oil single emulsions and in water/oil/water (w/o/w) double emulsions (DEs). In single emulsions new synchronization patterns are controlled by modulating the structural and chemical properties of the phospholipid-based membranes confining the BZ microoscillators. Changes are induced by introducing specific dopants that do not alter the basic backbone of the phospholipid bilayer but modify the membrane lamellarity or react with the chemical messengers. A transition from 2-period clusters (showing 1:2 resonance) to 1-period antiphase synchronization is observed by decreasing the membrane lamellarity, while an unsynchronized scenario is found when the dopant interferes with chemical communication. In the presence of multi-compartmentalized shells, after an initial induction period, all the oscillators pulsate in phase with halved period with respect to the starting one. The experimental dynamics are interpreted within a unique kinetic framework based on the Field, Köros and Noyes (FKN) model, including mass-exchange terms to modulate the coupling strength among successive oscillators. The impact of delayed feedbacks, that can spontaneously arise in the communication due to the confinement properties, are also numerically explored by including a time delay in the coupling terms. A direct transition from anti-phase to in-phase synchronization and back to the initial anti-phase scheme is observed by progressively increasing the time delay. Similarities of these phase transition scenarios with those characterising the coordination of oscillatory limb movements are also discussed.

Computer-assisted proof of the existence of renormalisation fixed points

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We prove the existence of fixed points to renormalisation operators for period doubling in maps of even degree at the critical point and for pairs of maps with a particular unidirectional coupling.

Our proof uses rigorous computer-assisted means to bound operations in a space of analytic functions and hence to show that quasi-Newton operators for the associated fixed-point problems are contraction maps on suitable balls.

By recasting the eigenproblems for the Frechet derivatives, we use the contraction mapping principle to gain rigorous bounds on eigenfunctions and their corresponding eigenvalues.

Our computations use multi-precision arithmetic with rigorous directed rounding modes to bound tightly the coefficients of the relevant power series and their high-order terms, and the corresponding universal constants.

The fractal structure of elliptical polynomial spirals

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We investigate fractal aspects of elliptical polynomial spirals, that is planar spirals with differing polynomial rates of decay in the two axis directions. This form of spiral reflects those that may form in anisotropic dynamical settings, such as elliptical whirlpools in a flowing body of water. We give a full dimensional analysis of these spirals, computing explicitly their intermediate, box-counting and Assouad-type dimensions. An exciting feature is that these spirals exhibit two phase transitions within the Assouad spectrum, the first natural class of fractals known to have this property. We go on to use this dimensional information to obtain bounds for the Holder regularity of maps that can deform one spiral into another, generalising the 'winding problem' of when spirals are bi-Lipschitz equivalent to a line segment. A novel feature is the use of fractional Brownian motion and dimension profiles to bound the Holder exponents.

Deep learning for early warning signals of bifurcations

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Many natural systems exhibit bifurcations where slowly changing environmental conditions spark a sudden shift to a new and sometimes very different state. As a bifurcation is approached, the dynamics of complex and varied systems simplify down to a limited number of possible 'normal forms' that determine qualitative aspects of the new state that lies beyond the bifurcation, such as whether it will oscillate or be stable. In several of those forms, indicators like increasing lag-1 autocorrelation and variance provide generic early warning signals (EWS) of the bifurcation by detecting critical slowing down. But they do not predict the type of bifurcation. Here, we develop a deep learning algorithm that provides EWS in systems it was not explicitly trained on, by exploiting information about normal forms and scaling behaviour of dynamics near tipping points that are common to many dynamical systems. The algorithm provides EWS in 268 empirical and model time series from ecology, thermoacoustics, climatology, and epidemiology with much greater sensitivity and specificity than generic EWS. It can also predict the normal form that characterises the oncoming tipping point, thus providing qualitative information on certain aspects of the new state. Such approaches can help humans better prepare for, or avoid, undesirable state transitions. The algorithm also illustrates how a universe of possible models can be mined to recognise naturally occurring tipping points.

Including synaptic plasticity in a next generation neural mass model

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Synaptic plasticity is considered the primary mechanism for learning and memory. Neurons with similar activity patterns strengthen their synaptic connections, while others connections may weaken. Synaptic plasticity is rarely examined at the mesoscopic level, as, typically, comparisons between spike times or firing rates of individual neurons are required to update the synaptic coupling strength. Assuming a network of synaptically coupled oscillators, we define spike time differences in terms of phase differences. We then update the synaptic connections based on these phase differences. Applying the Ott-Antonsen ansatz to the spatially distributed network lends itself to an exact mean-field description, in the form of a next generation neural mass model. This mean field model allows us to examine the role of synaptic plasticity at the mesoscopic level.

Nonlinear dynamics determines the thermodynamic instability of condensed matter in vacuo

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Condensed matter is thermodynamically unstable in a vacuum. That is what thermodynamics tells us through the relation showing that condensed matter at temperatures above absolute zero always has non-zero vapour pressure. This instability implies that at low temperatures energy must not be distributed equally among atoms in the crystal lattice but must be concentrated. In dynamical systems such concentrations of energy in localized excitations are well known in the form of discrete breathers, solitons and related nonlinear phenomena. It follows that to satisfy thermodynamics such localized excitations must exist in systems of condensed matter at arbitrarily low temperature and as such the nonlinear dynamics of condensed matter is crucial for its thermodynamics.

Effective models and predictability of chaotic multiscale systems via machine learning

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Understanding and modeling the dynamics of multiscale systems is a problem of considerable interest both for theory and applications. For unavoidable practical reasons, in multiscale systems, there is the need to eliminate from the description the fast/small-scale degrees of freedom and thus build effective models for only the slow/large-scale degrees of freedom. When there is a wide scale separation between the degrees of freedom, asymptotic techniques, such as the adiabatic approxi- mation, can be used for devising such effective models, while away from this limit there exist no systematic techniques. Here, we scrutinize the use of machine learning, based on reservoir comput- ing, to build data-driven effective models of multiscale chaotic systems. We show that, for a wide scale separation, machine learning generates effective models akin to those obtained using multiscale asymptotic techniques and, remarkably, remains effective in predictability also when the scale sep- aration is reduced. We also show that predictability can be improved by hybridizing the reservoir with an imperfect model.

Data-driven low-dimensional nonlinear models on spectral submanifolds

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Broadly used data-driven model reduction techniques only tend to be generally effective for linear dynamical systems. Available approaches to nonlinear systems use machine learning, which, however, comes with its sensitivities and limited potential for extrapolation or prediction outside the range of the input data. Here we discuss an approach to obtain explicit nonlinear models from data by exploiting the theory of spectral submanifolds. Our algorithm takes general observer data, without special assumptions on the measurement techniques or on the dimension of the data. The reduced-order models provide physical insights such as the nature of geometric nonlinearities or nonlinear damping in the system. The models we obtain are also powerful enough to make accurate predictions for the forced response of the nonlinear dynamical system solely based on numerical or experimental data from the unforced system. We illustrate these results on specific examples from structural vibrations and fluid dynamics, both on synthetic and experimental data.

The Retina as a Dynamical System

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Considering the retina as a high dimensional, non autonomous, dynamical system, layered and structured, with non stationary and spatially inhomogeneous entries (visual scenes), we present several examples where dynamical systems-, bifurcations-, and ergodic-theory provide useful insights on retinal behaviour and dynamics.

Low dimensional description of large oscillatory ensembles beyond the Ott-Antonsen manifold

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R. Cestnik and A. Pikovsky

A low dimensional description for infinite Kuramoto ensembles is derived involving an asymptotic series that describes their dynamics beyond the Ott-Antonsen manifold. This is achieved by expressing the dynamics in terms of circular cumulants and then recognizing that they represent a single non-linear differential equation in combination with an infinite linear system. The linear part can be solved thus closing the non-linear equation. This representation not only allows for more efficient numerical simulation, but also provides a new approach to analytically study the stability of the Ott-Antonsen manifold.

Emergent dynamics in a detailed, data-driven model of visual cortex

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L. Chariker, R. Shapley, and L.-S. Young

I will present work on a detailed, data-driven, spiking network model of macaque primary visual cortex (V1). The model covers 2 square millimeters of visual cortex and reproduces a number of its known phenomena. When driven, the network dynamics give rise to an emergent spike pattern with fluctuations like those seen in electrophysiological recordings, and we can look into mechanisms of how the fluctuations arise from the interactions between the excitatory and inhibitory populations in the network and how they are influenced by biophysical parameters. Experimental data from V1 in the literature has guided the construction of the model, from anatomical studies of connectivity to measurements of biophysical parameters and recordings showing spiking statistics in response to visual stimuli. This is joint work with Lai-Sang Young and Robert Shapley.

A comparison of a physics-based and data-driven inverse reconstruction technique of cardiac excitation wave patterns from mechanical deformation

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J. Christoph and J. Lebert

The contractions of the cardiac muscle are caused by nonlinear waves of electrical excitation. Because it is difficult to measure the electrical excitation within the volume of the cardiac muscle, it is compelling to ask whether the tissue deformation can be analyzed using an inverse numerical approach, such that the electrical excitation can be fully reconstructed. In this talk, I will discuss and compare two inverse numerical approaches, one physics-based and one deep learning-based approach, both of which aim to achieve the same goal of computing electrical excitation wave patterns from mechanical deformation. The two approaches were tested using synthetic data, which was generated in computer simulations of bulk-shaped elastic excitable media with anisotropic muscle fibre architecture. While the physics-based approach employed a replicate numerical model that assimilates mechanical observation data and had to be tuned carefully to match the original dynamics, the deep learning approach employed a convolutional neural network with an autoencoder-like architecture that was trained on many thousands of pairs of mechanical and corresponding electrical data. While both approaches can be used to successfully compute electrical excitation wave patterns from tissue deformation, our results show that deep learning outperforms the physics-based approach. Using deep learning, it becomes possible to predict even scroll wave chaos and their vortex filaments with high accuracy, even in the presence of noisy mechanical data and at low spatial resolutions.

Controllable complex oscillatory dynamics of the fundamental optomechanical oscillator

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S. Christou, V. Kovanis, A.E. Giannakopoulos and Y. Kominis

Cavity optomechanics is a research field of intense interest from a theoretical and technological point of view, having applications in sensitive optical detection and manipulation of small forces and displacements as well as topological energy transfer and phonon lasing [1]. The underlying models, describing the fundamental interaction between the electromagnetic radiation and small-scale mechanical motion, are known to exhibit a rich set of complex dynamical features including various types of chaotic behavior. However, technological applications in most cases necessitates a complex, yet predictable and controllable oscillatory response. In fact, the various types of robust oscillations supported by optomechanical systems are nested in the same or neighboring regions of the parameter space, where chaos exists. In this work we dissect the parameter space of the fundamental optomechanical oscillator to identify regions where stable self-sustained oscillations corresponding to limit cycles, and self-modulated oscillations, corresponding to limit tori, exist. A systematic bifurcation analysis is performed with the utilization of analytical and numerical continuation techniques. In cases of bistability, we study the accessibility of the oscillatory states in terms of the location of the initial conditions with respect to well defined basins of attraction [2]. Moreover, we identify the existence of Exceptional Points for the steady states of the system, and we investigate its modulation response under external parametric driving. The results provide specific knowledge for parameter sets enabling the appropriate oscillatory response for different types of applications.

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Emergence of complex spatiotemporal oscillations in large-scale brain networks

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Neural oscillations constitute a primary indicator of brain and cognitive function. How certain types of complex oscillatory patterns emerge from the intricate and multi-scale structure of the brain is an open problem of great interest in the quest to understand neural encoding and treat cognitive disorders through external stimulation.

In this work we unveil the emergence of chaotic oscillatory regimes in a large-scale model of the human brain cortex. The model consists of 90 brain regions connected through a complex network obtained from tractography data. The activity of each brain area is governed by the dynamics of a Jansen-Rit neural mass model. Despite the absence of heterogeneities and noise, the system displays irregular spatiotemporal oscillatory dynamics for a wide range of coupling strengths and subcortical external input values.

In order to determine the dynamical landscape of the system and understand the onset of irregular behavior, we first consider a simplified formulation in which the total input received by each node is the same across brain areas. This simplification allows for the existence of different stationary and oscillatory states in which all nodes behave identically. We study the stability properties of these homogeneous solutions in detail. In particular, by means of the master stability function, we unveil a Turing-like instability of the synchronized solution which gives rise to heterogeneous oscillatory states that ultimately lead to spatiotemporal chaos.

Next, extensive numerical simulations of the original system reveal that irregular oscillations emerge through a mechanism similar to that of the simplified formulation, but differ on how the patterns synchronize and travel across the network.

Overall, our work characterizes a simple framework for the emergence of complex dynamics in systems composed of interconnected neural mass models.

Quasicrystal patterns in a neural field model

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Neural field models of the activity in primary visual cortex (V1) are pattern forming systems that incorporate non-local axonal wiring. A coarse grained view of V1 with short-range neuronal interactions that are excitatory and long-range ones that are inhibitory is well known to support a Turing instability to doubly-periodic patterns. Here we show that a modulation of this connectivity structure can lead to the formation of quasicrystal patterns, thus expanding the repertoire of drug induced geometric hallucinations that can be explained by a Turing mechanism.

Long-Time Behavior of a PDE Replicator Equation for Multilevel Selection in Group-Structured Populations

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D.B. Cooney and Y. Mori

In many biological systems, there is an evolutionary conflict between the incentive of individuals to cheat and the collective incentive to establish cooperation within groups of individuals. In this talk, we consider a hyperbolic PDE describing the evolutionary dynamics of a two-level birth-death process in which individual-level replication favors cheaters and between-group competition favors groups featuring positive levels of cooperation. We derive a threshold level of the relative strength of between-group competition such that defectors take over the population below the threshold while cooperation weakly persists in the long-time population above the threshold. Under stronger assumptions on the initial distribution of group compositions, we further prove that the population converges to a steady state density supporting cooperation for between-group selection strength above the threshold. When the group replication rate is maximized by an intermediate level of cooperation, we additionally see that the average payoff at steady state is limited by the average payoff a full-cooperator group, and that the steady state density concentrates to a delta-function supporting a suboptimal level of cooperation in the limit of infinite strength of between-group competition. In these cases, individual-level selections casts a long shadow on the dynamics of multilevel selection: no level of between-group competition can erase the effects of the individual incentive to defect.

Properties of the extended time-delayed feedback control under model mismatches

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The stability analysis in delayed systems presents several challenges. The methods used for such analysis usually involve calculating Lyapunov exponents of a system hundreds of times greater than the original and can only extract the real part of these exponents. An alternative to this type of approach is the application of Floquet theory which is constructed to deal with periodic systems. This approach maintains the dimension of the system's state space and provides both real and complex parts of the Floquet exponents, which enriches the analysis. Floquet exponents have been already used to analyse the properties of the extended time-delayed feedback control with great success and can be applied to other types of delayed systems. This work deals with the application of Floquet theory to analyse how model imprecisions and time delay affect the extended time-delayed feedback control effectiveness to stabilise a periodic orbit. Results show that the approach can be used to predict the control parameters that can stabilise the target orbit. Also, it is observed that the controlled orbit stability is affected in different ways depending if imprecisions are considered on actual or delayed states. Finally, the methods described are applied to an SMA pendulum system controlled by the extended time-delayed feedback method to set control parameters.

Forecasting turbulence in a passive resonator with supervised machine learning

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Predicting complex nonlinear dynamical systems has been even more urgent because of the emergence of extreme events such as earthquakes, volcanic eruptions, extreme weather events (lightning, hurricanes/cyclones, blizzards, tornadoes), and giant oceanic rogue waves, to mention a few. The recent milestones in the machine learning framework offer a new prospect in this area [1, 2]. For a high-dimensional chaotic system, increasing the system's size causes an augmentation of the complexity and, finally, more nodes in the network. Here, we propose a new supervised machine learning strategy to forecast bursts occurring in the turbulent regime of a fiber ring cavity. An interesting feature of this turbulent evolution is the persistent long-range correlation in the dynamics[3]. The system can then be seen as adjacent subdomains. Owing to this feature, instead of predicting the whole system, we use appropriate tools of chaos theory to identify recurrent pictures in the past at the same location of the bursts. We were able to identify in the past causal information of the present. We have taken advantage of the apparent causality to make an association precursors-pulses. We can then forecast with high accuracy the location of the bursts for a predetermined horizon. Then, knowing when and where the bursts emerge, a fair question is "What will be observed?”. As the statistics fail to answer this question, we have implemented a machine learning strategy. Finally, we can accurately forecast the profile of the incoming bursts with an artificial neural network.

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Circadian Re-entrainment Dynamics Organised by Global Invariant Manifolds

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Circadian rhythms are established by the entrainment of the internal body clock to the 24 hour period of the external environment. If a clock becomes phase shifted, e.g. via international travel or shift work, it may re-entrain over several days in a complex and highly sensitive manner. In this talk, we consider the loss of entrainment and the dynamics of re-entrainment in a two-dimensional model of the human circadian pacemaker forced by a 24-hour light/dark cycle. We characterise the loss of entrainment by continuing bifurcations of one-to-one entrained orbits under variation of external forcing parameters, and intrinsic clock period. We show that the ‘severity’ of the loss of entrainment is dependent on the type of bifurcation inducing the change of stability of the entrained orbit. We further show that for certain perturbations the model predicts a counter-intuitive rapid re-entrainment if light intensity is sufficiently high. We explain this phenomenon via computation of global invariant manifolds of fixed points of a 24-hour stroboscopic map. Finally, we show how the manifolds organise re-entrainment times following transitions between day and night shift work.

Homoclinic classes of surface dynamics

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It is well-known that the dynamics of uniformly hyperbolic systems decomposes into finitely many transitive pieces (the basic sets). A natural generalization for the decomposition of non-uniformly hyperbolic systems are the homoclinic classes. I will present recent results that allows to describe the dynamics of arbitrary surface diffeomorphisms, up to neglect sets having zero entropy: in particular, I will discuss the construction of symbolic codings of each class and the properties of the equilibrium measures.

Stochastic switching between oscillation patterns: combining stochastic delays and additive phase noise

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Many network systems of various nature exhibit temporal delays accounting for the travelling time of a propagating signal. Coupling delays arise in laser physics, neuroscience, gene regulatory networks, traffic and population dynamics, communication networks, etc. A typical effect of time delays is multistability: different types of dynamics are possible for the same parameters. Hence, stochastic perturbations, which are present in any real-life system, can cause hopping between coexisting stable states. We investigate these modes hopping dynamics in small network motifs, in which different oscillation patterns coexist. We utilize a model of a pulse-coupled phase oscillator, which is both simple and widely used for between others, biological oscillators. Both numerically and in an electronic experimental setup, we implement two types of noise: i) additive phase noise acting on the oscillator state variable and ii) stochastic fluctuations of the coupling delay. We find that the system shows dramatically different scaling properties for different types of noise. While the robustness to conventional phase noise increases exponentially with the coupling strength, for stochastic variations in the coupling delay, the lifetimes decrease with the coupling strength. Combining these two types of noise, there is a coupling strength for which the robustness to noise is optimal. We provide an analytical explanation for these scaling properties in a linearized model. Our findings thus indicate that the robustness of a system to stochastic perturbations strongly depends on whether the perturbation is applied to the nodes – the oscillators - or to the links – the delay lines - in a network.

Gap junctions in basal ganglia — a conceptual model

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Montbrió et al. (PRX 5(2), 021028) provided an exact dynamics of the firing rate and the mean membrane potential of a population of quadratic integrate and firing neurons. In the wake of this seminal study, Pietras et al. (PRE 100(4), 042412) discussed the role of gap junctions in this mean field dynamics and highlighted how they can promote synchronization. This is particularly interesting because it may help understanding the emergence of pathological neural oscillation in neurodegenerative diseases like Parkinson's. There, the reciprocal circuit of the globus pallidus externa and the subthalamic nucleus is known to display low-frequency oscillations ($\sim$15-30 Hz). With a focus on the oscillatory regime, here, the Pietras et al. model is extended by an external (e.g., striatal) drive. This may lead to mere resonances but also to period doubling bifurcations en route to chaos. Furthermore, the case of two mean-field dynamics is discussed when coupled through chemical synapses. Potentially this may cause (low-frequency) synchronization between the two neural populations, similar to what has been experimentally observed between globus pallidus externa and subthalamic nucleus.

Information and thermodynamics: fast and precise approach to the Landauer's bound in an underdamped micro-mechanical oscillator

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The Landauer's principle states that at least $k_B T_0 \ln 2$ of energy is required to erase a 1-bit memory, with $k_B T_0$ the thermal energy of the surrounding bath. Practical erasures implementations require an overhead to the Landauer's bound, observed to scale as $k_B T_0 \times B/\tau$, with τ the protocol duration and B close to the system relaxation time. Most experiments use overdamped systems, for which minimizing the overhead means minimizing the dissipation. Underdamped systems, never harnessed before, thus sounds appealing to reduce this energetic cost.

We use as one-bit memory an underdamped micro-mechanical oscillator confined in a double-well potential created by a feedback loop. The potential barrier is precisely tunable in the few $k_B T_0$ range. We measure, within the stochastic thermodynamic framework, the work and the heat of the erasure protocol. We demonstrate experimentally and theoretically that, in this underdamped system, the Landauer's bound is reached within a 1% uncertainty, with protocols as short as 100ms.

Besides, we show that for such underdamped systems, fast erasures induce a heating of the memory: the work influx is not instantaneously compensated by the inefficient heat transfert to the thermostat. This temperature rise results in a kinetic energy contribution superseding the viscous dissipation term. Our model covering all damping regimes paves the way to new optimisation strategies in information processing, based on the thorough understanding of the energy exchanges. Indeed we are able to quantify the overhead to the Landauer's bound depending on the system and protocol parameters, and to identify the origins of this energy cost.

Secular and hyperbolic dynamics of Molniya satellites semi-major axis

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We describe the phase space structures related to the semi-major axis of Molniya-like artificial satellites subject to tesseral and lunisolar resonances. In particular, we dissect the indirect interplay of the critical inclination resonance on the semi-geosynchronous resonance using a hierarchy of more realistic dynamical systems, thus discussing the dynamics beyond the integrable approximation. By introducing secular (averaged over fast angles of systems) models, we numerically demarcate the hyperbolic structures organising the phase space via the computation of Fast Lyapunov Indicators. Based on the publicly available two-line elements space orbital data, we identify two satellites, namely M1-69 and M1-87, displaying fingerprints consistent with the dynamics associated to the hyperbolic set. The computations of the associated dynamical maps highlight that the spacecraft are trapped within the hyperbolic tangle.

Dynamics in the learning of dynamical systems

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Learning of dynamical systems from partial observations is one of the oldest challenges in this field. Broadly, there are two tasks - extracting the full dynamical information from the partial observation; and then to learn the dynamics from the embedding. We present a mathematical framework in which both these tasks are represented using one commutative diagram. The scheme represented by this diagram contains as special cases all common learning techniques, such as using delay-coordinates or reservoir computing. Besides providing a unification of widely different techniques, our framework also provides the platform for two other investigations of the reconstructed system - its dynamical stability; and the growth of error under iterations. We show that these questions are deeply tied to more fundamental properties of the underlying system - the behavior of matrix cocycles over the base dynamics, non-uniform hyperbolic behavior, its Lyapunov exponents, and its decay of correlations.

Complex dynamics of redox reactions on nanosized catalyst samples

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Automotive pollution control crucially relies on the reactivity of metal and metal alloy catalysts. Understanding how the chemistry of an alloy compares with that of pure metals forms a decisive step towards the rational development of applied formulations of such catalysts.

In this context, we studied the hydrogenation of NO and NO2 on Pt and Pt-Rh catalysts at the nanoscale with field emission microscopy (FEM). Complex reaction kinetics, including periodic and multiperiodic oscillations, were observed in all cases.

However, the range of temperature where these behaviors were detected depends strongly on the composition of the catalyst. Pure Pt samples showed oscillations at 390 K, while for pure Rh samples a temperature of at least 500 K was needed. Alloys presented similar oscillations at intermediate temperatures, depending on their composition. The role of the alloy composition on the window of reactivity is explained with a simple theoretical model for the kinetics of the reaction.

Stability of pattern-forming fronts with a quenching mechanism

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B. de Rijk and R. Goh

Pattern-forming fronts invading a destabilized ground state in spatially homogeneous systems are generally considered unstable as any perturbation ahead of the front grows exponentially in time due to the instability of the ground state. Nevertheless, pattern-forming fronts are observed in various spatially inhomogeneous settings such as light-sensing reaction-diffusion systems, directional solidification of crystals or ion beam milling. In these settings the unstable state is only established in the wake of the heterogeneity after which patterns start to nucleate. Consequently, perturbations cannot grow far ahead of the interface of the pattern-forming front. This begs the question of whether stability can be rigorously established. In this talk, I answer this question affirmative by presenting a stability result for pattern-forming fronts against L^2-perturbations in the spatially inhomogeneous complex Ginzburg-Landau equation. A technical challenge is posed by the presence of unstable absolute spectrum which prohibits the use of standard tools such as exponential dichotomies. Instead, we projectivize the linear flow and study the associated matrix Riccati equation on the Grassmannian manifold. Eigenvalues can then be identified as the roots of the meromorphic Riccati-Evans function. This is joint work with Ryan Goh (Boston University).

Turbulent-like Dynamics in the Human Brain

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Turbulence is a special dynamical state driving many physical systems by way of its ability to facilitate fast energy/information transfer across scales. These qualities are important for brain function, but it is currently unknown if the brain also exhibits turbulence as a fundamental organisational principle. Using large-scale neuroimaging data from

1003 healthy participants, we demonstrate both empirically and through the use of a computational whole-brain model that human brain dynamics is organised around a turbulent homogeneous isotropic functional core. We show the economy of anatomy of this functional core following the exponential distance rule of anatomical connections as a cost-of-wiring principle, which displays a turbulent-like power scaling law for functional correlations in a broad spatial range suggestive of a cascade of information processing. Further investigating this, we use the theory of turbulence in coupled oscillators in a whole-brain model to demonstrate that the best fit of our model to the data corresponds to a region of maximally developed amplitude turbulence, which also corresponds to maximal sensitivity to the processing of external stimulations (information capability). This establishes a firm link between turbulence and optimal brain function. Overall, our results reveal a novel way of analysing and modelling whole-brain dynamics that for the first time ever establishes turbulence as a fundamental basic principle of brain organisation.

Self-sustained shear driven Hall MHD dynamos

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The Hall effect on an MHD dynamo driven by shear is studied. As with many turbulent transitions in purely hydrodynamic shear flows, whether a dynamo is generated or not must be treated in the framework of a subcritical transition problem, for which dynamical systems theory is useful. We focus on the steady-state solution that seems to be at the edge of basin of attraction of dynamo turbulence, and derive its behavior at high Reynolds numbers by matched asymptotic expansion. The structure of the solution is described by the interaction between the mean field and current sheets. Its overall framework is somewhat similar to that of mean field theory, but it does not require any artificial assumptions for closure.

Mean-field synchronization in multiplex networks

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Many biological and technological complex systems can be represented as dynamical multiplex networks, where the same nodes interact within different layers. The features of the synchronized state provide important information about the system, and therefore their study is especially important in view of potential applications. In particular, assessing the stability of the global synchronization is a fundamental step in understanding the interplay between structure and dynamics. To this purpose, one can apply a generalization of the master stability function approach, which yields a system of coupled differential equations for the global synchronization error. However, computing the derivatives in this system has a computational complexity of $O(N^3M)$, where N is the number of nodes and M is the number of layers. This makes it potentially unwieldy on very large systems. Here, we propose a mean-field perturbative theory of the multiplex synchronization, which we derive in the assumption of quasi-identical layers. This approach produces a system of equations that is a first-order correction to the case of commuting graph Laplacians. In turn, this reduces the complexity of computing each component of the global synchronization error to $O(NM)$. We also show by theoretical argument and numerical simulations that the error committed in estimating the largest Lyapunov exponent of the synchronization error decreases with system size. In addition, we show that the number of wrong assessments of the stability of the synchronized state is vanishingly small even for normalized dynamical distances between the layers as high as 0.2. This makes our new method a preferred tool to provide a fast and accurate estimate of the linear stability of synchronization in multiplex networks.

Emergence of collective oscillations in balanced neural networks due to endogeneous fluctuations

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We present a transition from asynchronous to oscillatory behavior in balanced inhibitory networks for class I and II neurons with instantaneous synapses. Collective oscillations emerge for sufficiently connected networks. We show that microscopic irregular firings, due to balance, is a necessary ingredient to trigger sustained oscillations. The same mechanism induces in balanced excitatory-inhibitory networks quasiperiodic collective oscillations. Finally, we show that a mean field approach based on the Fokker-Planck equation is able to correctly predict network dynamics, both in asynchronous and in oscillatory regimes.

Levels for properties of topological dynamical in the Context of Cellular Automatas

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M. Diaz and D.Carrasco

Here below we present some main concepts and dynamic results in metric spaces corresponding to Cellular Automatas. Mainly, our results focus on different topological levels, such as transitivity, mixing, sensitivity to initial conditions, and expansiveness. Finally, using Furstenberg families, we are going to show a relationship between these levels for dynamical systems that have maps with pseudo-orbit tracing properties and connected spaces.

Data-Driven Prediction of Crowd Mobility through Koopman Operator Approximation

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D. Lehmberg, F. Dietrich and G. Köster

Data-driven modeling and forecasting of complex spatio-temporal patterns in traffic systems is a challenge. After providing a short introduction to the Koopman operator and its numerical approximation, we demonstrate that the framework allows modeling, forecasting, and interpretable results for the openly available pedestrian traffic data from Melbourne, Australia. In a multi-sensor setting, we perform 24-hour predictions of the pedestrian counts at eleven sensors across the city. We discuss how spatio-temporal patterns intrinsic to the system can be extracted from the model in the form of eigenfunctions of the operator, and what insights they provide into the pedestrian traffic of Melbourne.

Approximating normally attracting invariant manifolds using a trajectory-based optimization approach

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Normally attracting invariant manifolds (NAIMs) are concerned with the long-term behavior of dissipative dynamical systems. While most numerical approximation methods exploit the persistence property of uniform NAIMs our approach concentrates on their geometry to provide a family of invariant manifolds clustering around NAIMs. It does not require the existence of the so-called critical manifold and is formulated for semiflows on Riemannian manifolds. This setting is natural for adiabatic systems in chemical kinetics, which we used to test our findings. Our theoretical results are currently limited to one-dimensional submanifolds. A generalization for higher dimensions could be achieved through a curvature-based variational approach.

Generalizing the Unscented Ensemble Transform to Higher Moments

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D. Easley and T. Berry

We develop a new approach for estimating the expected values of nonlinear functions applied to multivariate random variables with arbitrary distributions. Rather than assuming a particular distribution, we assume that we are only given the first four moments of the distribution. The goal is to efficiently represent the distribution using a small number of quadrature nodes which are called σ-points. What we mean by this is choosing nodes and weights in order to match the specified moments of the distribution. The classical scaled unscented transform (SUT) matches the mean and covariance of a distribution. In this paper, we introduce the higher order unscented transform (HOUT) which also matches any given skewness and kurtosis tensors. It turns out that the key to matching the higher moments is the tensor CP decomposition. While the minimal CP decomposition is NP-complete, we present a practical algorithm for computing a non-minimal CP decomposition and prove convergence in linear time. We then show how to combine the CP decompositions of the moments in order to form the σ-points and weights of the HOUT. By passing the σ-points through a nonlinear function and applying our quadrature rule we can estimate the moments of the output distribution. We prove that the HOUT is exact on arbitrary polynomials up to fourth order and derive error bounds in terms of the regularity of the function and the decay of the probability. Finally, we numerically compare the HOUT to the SUT on nonlinear functions applied to non-Gaussian random variables including an application to forecasting and uncertainty quantification for chaotic dynamics.

A motif in the regulation of plant metabolism and piecewise-linear approximation of biochemical networks

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Biochemical networks often take the form of systems of ODEs with Michaelis-Menten interactions. A motif that arises in at least one such network, for the regulation of metabolism in plants, is the Precursor Shutoff Valve (PSV). Primary metabolism must be maintained at a steady (if low) level, while secondary metabolism (production of lignin to build wood in trees, for example) can be very highly active, when input is plentiful, but can be shut off completely when input is low. However, both pathways are fed by the same chain of input reactions. Two possible mechanisms by which a plant may differentially regulate the two output fluxes have recently been proposed. One is simply a difference in thresholds for the two output pathways; the other is the PSV, a motif in which a precursor of both pathways is required for a reaction in the secondary pathway only. The combination of the two mechanisms is the most effective. Analysis of such a system is facilitated by a piecewise-linear approximation of the Michaelis-Menten type interactions, comprising a linear region followed by a saturated (constant) region. It is likely that the PSV motif occurs in other contexts, but interestingly, it is not effective in steep-switching systems (like Glass networks), where on the other hand the effect of threshold separation is most clear. All of these results can be proven analytically.

Pattern formation can enable species coexistence in resource-limited ecosystems

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Self-organised spatiotemporal patterns are ubiquitous in nature. Prime examples include dryland vegetation patterns, intertidal mussel beds and Subalpine ribbon forests. Despite the pattern's occurrence under severe environmental stress, species coexistence is commonly observed. In this talk, I argue that the spatial self-organisation principle also acts as a coexistence mechanism. To this end, I present a bifurcation analysis of a PDE model for two consumer species interacting with a sole limiting resource, based on the Klausmeier reaction-advection-diffusion system. Patterned solutions occur as periodic travelling waves and thus theory on limit cycles in dynamical systems can be utilised in the analysis. Firstly, a stability analysis of the system's single-species patterns, performed through a calculation of their essential spectra, provides an insight into the onset of coexistence states. I show that coexistence solution branches bifurcate off single-species solution branches as the single-species states lose their stability to the introduction of a second species. Secondly, I present a comprehensive existence and stability analysis to establish key conditions, including a balance between the species' local competitive abilities and their colonisation abilities, for species coexistence in the model. Finally, I show that the inclusion of intraspecific competition dynamics has a significant impact on the coexistence mechanism and the system's bifurcation structure in general.

On Hopf bifurcations in MAPK signaling systems

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In this talk I will discuss the source of oscillations in a well-known model of the MAPK signaling cascade. The modelled mechanism consists of three phosphorylation layers, such that the first layer comprises a single phosphorylation cycle, while the other two correspond to double phosphorylation cycles. With mass-action kinetics, this mechanism gives rise to oscillations. The source of oscillations has been previously attributed to the bistability of the second layer in combination with the first layer. In this talk I will show that the cascade structure is enough, and a simpler cascade with two layers of single phosphorylation cycles already admits oscillations. The techniques behind the result are based on the computation of the so-called Hurwitz determinants, which are huge polynomials, and the analysis of the signs they attain over the positive orthant. This work is joint with A. Torres.

Quantifying dynamic stability and signal propagation: Lyapunov spectra of recurrent neural networks

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Brains process information through the collective dynamics of large neural networks. Collective chaos was suggested to underlie the complex ongoing dynamics observed in cerebral cortical circuits and determine the impact and processing of incoming information streams. In dissipative systems, chaotic dynamics takes place on a subset of phase space of reduced dimensionality and is organized by a complex tangle of stable, neutral and unstable manifolds. Key topological invariants of this phase space structure such as attractor dimension, and Kolmogorov-Sinai entropy so far remained elusive.

Here we calculate the complete Lyapunov spectrum of recurrent neural networks. We show that chaos in these networks is extensive with a size-invariant Lyapunov spectrum and characterized by attractor dimensions much smaller than the number of phase space dimensions. We find that near the onset of chaos, for very intense chaos, and discrete-time dynamics, random matrix theory provides analytical approximations to the full Lyapunov spectrum. We show that a generalized time-reversal symmetry of the network dynamics induces a point-symmetry of the Lyapunov spectrum reminiscent of the symplectic structure of chaotic Hamiltonian systems. Fluctuating input reduces both the entropy rate and the attractor dimension. For trained recurrent networks, we find that Lyapunov spectrum analysis provides a quantification of error propagation and stability achieved. Our methods apply to systems of arbitrary connectivity, and we describe a comprehensive set of controls for the accuracy and convergence of Lyapunov exponents.

Our results open a novel avenue for characterizing the complex dynamics of recurrent neural networks and the geometry of the corresponding chaotic attractors. They also highlight the potential of Lyapunov spectrum analysis as a diagnostic for machine learning applications of recurrent networks.

Rotating waves: from local discrete systems to nonlocal continuous media

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In two or more spatial dimensions, oscillatory and excitable media are able to produce spiral and other types of rotating behavior. We start with a system of locally coupled phase oscillators on an NxN grid and show that when the coupling includes non-odd components, spiral waves emerge. We show that as $N \to \infty$, that the dynamics can be understood by a Burgers type equation on an annulus with inner radius proportional to 1/N. We then turn to nonlocal coupling on an annulus and show that rotating waves solve a certain one-dimensional integral equation. We investigate the stability of the waves and connect an instability as the inner radius of the annulus shrinks to the formation of so-called chimeras.

Studying phase variability and synchronization in the dynamics of electroencephalographic recordings from epilepsy patients

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A. Espinoso and R. G. Andrzejak

About 1% of the world population suffers from epilepsy, a severe neurological disorder. Electroencephalographic recordings (EEG) from epilepsy patients help clinicians in assessing the brain dynamics for a possible diagnostics. For patients who suffer from pharmacoresistant focal epilepsy, the purpose of EEG analysis is the localization of the brain area causing the seizures, the so-called seizure onset zone (SOZ) which can then be surgically resected. We use the public domain Bern-Barcelona database, formed by two main groups of signals: one set recorded from the hemisphere that contains the SOZ (focal signals) and the other set recorded from the other hemisphere (nonfocal signals). This database was composed in 2012 (Andrzejak, Schindler and Rummel, Physical Review E 86, 046206, 2012). The recordings from this database are seizure-free, meaning that we do not have the actual seizure activity. In this work we evaluate different analysis techniques based on the instantaneous phases extracted from the signals. As a result, we can detect features induced by epilepsy present in individual signals or manifest themselves between pairs of signals. Here we study the phase variability from individual signals, using the phase diffusion coefficient, and the phase synchronization from pairs of signals, using the mean phase coherence. We design a test from this phase-based signal analysis techniques jointly with the concept of surrogates. We first apply these phase-based techniques to the Rössler model system to understand how these measures work under controlled conditions. Our results from the EEG show that focal signals have more phase synchronization and less phase variability than nonfocal signals. The highest contrast is found applying the phase diffusion test. In conclusion, the phase-based measures which are obtained by simple definitions give relevant information about the underlying dynamics in EEG signals, being helpful for the presurgical evaluation of epilepsy.

Enhanced wave damping in a sloshing experiment: the weakly non-linear case

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We report on the enhancement of the hydrodynamic damping of weakly nonlinear surface gravity waves at as they interact with a turbulent vortex flow in a sloshing experiment. Gravity surface waves are excited by oscillating horizontally a square container holding our working fluid (water). At the bottom of the container, four impellers in a quadrupole configuration generate a vortex array at moderate to high Reynolds number, which interact with the wave. We measure the surface fluctuations using different optical nonintrusive methods and the local velocity of the flow using a simple PIV scheme. In our experimental range, we show that as we increase the angular velocity of the impellers, the gravity wave amplitude decreases without changing the oscillation frequency or generating transverse modes. Furthermore, as we increase the wave amplitude, the nonlinear resonance curve observed for the surface gravity wave (which displays hysteresis) becomes single valued and diminishes its maximum amplitude. This wave dissipation enhancement is contrasted with the increase of the turbulent velocity fluctuations from particle image velocimetry measurements via a turbulent viscosity. To rationalize the damping enhancement a periodically forced shallow water model including viscous terms and weak nonlinearity is presented, which is used to calculate the sloshing wave resonance curve. A reasonable agreement is found between the model's predictions and the observed qualitative and quantitative features of the damped surface wave.

Asymptotic Estimates of Sars-CoV-2 Infection Counts and Their Sensitivity to Stochastic Perturbation in SEIR Models

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Despite the importance of having robust estimates of the time-asymptotic total number of infections, early estimates of COVID-19 show enormous fluctuations. Using COVID-19 data from different countries, we show that predictions are extremely sensitive to the reporting protocol and crucially depend on the last available data point before the maximum number of daily infections is reached. We propose a physical explanation for this sensitivity, using a susceptible–exposed–infected–recovered model, where the parameters are stochastically perturbed to simulate the difficulty in detecting patients, different confinement measures taken by different countries, as well as changes in the virus characteristics. Our results suggest that there are physical and statistical reasons to assign low confidence to statistical and dynamical fits, despite their apparently good statistical scores. These considerations are general and can be applied to other epidemics. With these caveats in mind we extrapolate the long-term behavior of the epidemics in both countries using a Susceptible-Exposed-Infected-Recovered (SEIR) model where parameters are stochastically perturbed with a log-normal distribution to handle the uncertainty in the estimates of COVID-19 prevalence, to simulate the presence of super-spreaders, the dynamics of epidemic waves and the risks/benefits of a vaccination campaign.

Thermalization of a rarefied gas with total energy conservation

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The thermalization of a gas towards a Maxwellian velocity distribution with the background temperature is described by a kinetic relaxation model. The sum of the kinetic energy of the gas and the thermal energy of the background are conserved, and the heat flow in the background is governed by the Fourier law. For the coupled nonlinear system of the kinetic and the heat equation, existence of solutions is proved on the one-dimensional torus. Spectral stability of the equilibrium is shown on the torus in arbitrary dimensions by hypocoercivity methods. The macroscopic limit towards a nonlinear cross-diusion problem is carried out formally.

Simple Control for Complex Pandemics

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Amidst the current COVID-19 pandemic, quantifying the effects of strategies that mitigate the spread of infectious diseases is critical. This article presents a compartmental model that addresses the role of random viral testing, follow-up contact tracing, and subsequent isolation of infectious individuals to stabilize the spread of a disease. We propose a branching model and an individual (or agent) based model, both of which capture the stochastic, heterogeneous nature of interactions within a community. The branching model is used to derive new analytical results for the trade-offs between the different mitigation strategies, with the surprising result that a community's resilience to disease outbreaks is independent of its underlying network structure.

Invariant measures for stochastic 2D damped Euler equations

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We consider the 2D damped Euler equations with additive noise. When the noise is smooth in space, we define a Markov semigroup in the space L^∞ equipped with the weak-* topology and prove existence of invariant measures by means of a modified Krylov-Bogoliubov's method.

Chimera-like states in Lugiato-Lefever equation

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The Lugiato-Lefever equation, derived in 1987 for Luigi Lugiato and René Lefever, has become one of the most important models in nonlinear optics, specifically to describe the dynamical properties of electric fields confined to optical cavities and resonators. In this contribution, we show the existence of chimera-like states in the Lugiato Lefever equation. Chimera-like states correspond to solutions that exhibit coexistence between coherence and incoherence behaviors. To characterize these states, we use Lyapunov exponents, Fourier spectrum, and Yorke-Kaplan dimension, standard tools in studying chaotic systems. The complex spatiotemporal dynamics showed an intermittent nature[1,2].

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Transient chaos in complex networks: Desynchronization and state-dependent vulnerability

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We analyze the final state sensitivity of nonlocally coupled networks of Duffing oscillators. By changing the initial conditions of a single network unit, we perturb an initially synchronized state, which is the only attractor for a single unit. Depending on the perturbation strength, we observe the existence of two possible network long-term states: (i) The network neutralizes the perturbation effects and returns to its synchronized configuration. (ii) The perturbation leads the network to an alternative desynchronized state. By computing the uncertainty exponent of a two-dimensional cross section of the state space, we find the existence of a fractal set of initial conditions converging to this desynchronized solution, which appears to be either a new attractor or a chaotic saddle, i.e. an unstable chaotic set on which trajectories persist for extremely long times. Furthermore, we report the existence of an intricate time dependence of the vulnerability of the synchronized state in a network composed of identical electronic circuits. By perturbing the synchronized dynamics in consecutive instants of time, we find that synchronization breaks down for some time instants while it persists for others. The mechanism behind this intriguing phenomenon is again the existence of an unstable chaotic set close to the synchronized trajectory. Both phenomena highlight the crucial role played by unstable chaotic set leading to transient chaotic dynamics in networked systems. We discuss that these phenomena are generic for large classes of nonlinear dynamical systems.

Numeric model of experimental front microrheology using a non-linear Klein-Gordon equation

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In this research, we propose a numeric model to study an experimental front microrheology using a non-linear Klein-Gordon equation and the ϕ^4 model, given by the potential $V(u) = \frac{1}{2}(u^2 - 1)^2$. The experimental system is a microfluidic device that uses an optical detection method to tracking the fluid-air interface moving inside a microchannel with an imperfection. We model this behavior with a differential equation that includes a constant force f_0, a localized force $F(x, y)$ to model the imperfection, and a dissipative term given by $-\gamma\partial_t u(x, t)$, with u a field. The system is described by the equation $\partial_{tt}u - \partial_{xx}u - \gamma\partial_t u(x, t) + \frac{1}{2}(u - u^3) = f_0 + F(x, y)$.

From seeing double to chaotic itinerancy with a multifunctional reservoir computer

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The ability of a neural network to perform more than one task is known as multifunctionality. In this talk we will explore some of the phenomena which arise when translating multifunctionality from the biological world to an artificial setting using the reservoir computer (RC) approach to machine learning. As a paradigmatic example of multifunctionality, we examine the dynamics of the RC when it is trained to simultaneously imitate trajectories along two overlapping circular orbits rotating in opposite directions. By virtue of this experiment's simplicity, we are able to place a greater emphasis on understanding the necessary conditions for multifunctionality to occur in a RC. We expose the intricate relationship between multifunctionality and the spectral radius of the RC's internal connections, a parameter associated with the RC's memory. Particular attention is given to the extreme case where the circular orbits are completely overlapping in space. A bifurcation analysis reveals that multifunctionality emerges through the evolution of 'untrained attractors' and is destroyed as the RC crosses the edge of chaos. As multifunctionality breaks down nearby this boundary we observe chaotic itinerancy as the state of the RC wanders between attractor ruins.

Estimates on return and mixing for the $\mathbb{Z}^d$-periodic Lorentz gas with infinite horizon (d=1 or d=2)

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The Lorentz gas models the evolution of a point particle moving at unit speed with elastic collisions off strictly convex and smooth obstacles (e.g. disks). We assume that the configuration of obstacles is periodic. We consider the case of a $\mathbb{Z}^2$-periodic configuration in $\mathbb{R}^2$, as well as the case of a $\mathbb{Z}$-periodic configuration on a tube. We assume that the horizon is infinite, meaning that there exist corridors in which the particle can go to infinity without meeting any obstacle. In this case, the free flight function between two successive collisions is not bounded, and not even square integrable. For this model, Domokos Szász and Tamás Varjú proved the central limit theorem (CLT) and the local limit theorem (LLT) for the free flight function, with a nonstandard normalization (with an additional $\log$). These results play a crucial role in the study of recurrence and mixing properties of the periodic Lorentz gas. We will present further results in this direction, such as an asymptotic estimate for the tail probability of the first return time to the initial cell, higher order estimates in the mixing LLT, more precise mixing estimates with different results depending whether the integrals are null or not. These new results are based on precise (and delicate) estimates on the dominated eigenvalue (and on the corresponding eigenprojector) of Fourier operators, and also on some geometric arguments (appearing e.g. in an estimate of the probability of a long free flight in a corridor). This is a joint work with Dalia Terhesiu.

Design Principles of Protein Patterns

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Protein pattern formation is essential for the spatial organisation of many intracellular processes like cell division, flagellum positioning, and chemotaxis. A prominent example of intracellular patterns are the oscillatory pole-to-pole oscillations of Min proteins in E. coli whose biological function is to ensure precise cell division. Cell polarisation, a prerequisite for processes such as stem cell differentiation and cell polarity in yeast, is also mediated by a diffusion–reaction process. More generally, these functional modules of cells serve as model systems for self-organisation, one of the core principles of life. Under which conditions spatio-temporal patterns emerge, and how these patterns are regulated by biochemical and geometrical factors are major aspects of current research. In this talk we discuss recent theoretical and experimental advances in the field of intracellular pattern formation, focusing on general design principles and fundamental physical mechanisms.

Long Wavelength Coherence in Well-Connected Power Grids

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Power grids are standardly modeled as coupled oscillators where each oscillator represents an electric generator or a load. It has been observed that groups of generators in one area sometimes start to oscillate coherently against a geographically separated group of generators in a different area. Such long wavelength coherent effects are well-understood in networks that consist of weakly-coupled well-defined areas. However, these oscillations have also been observed in large scale power grids. We find for example, that in a model of the European high voltage grid the generators in Spain and Portugal respond coherently to a noisy perturbation in Greece. These Inter-area oscillations are problematic because they can lead to grid instabilities. It is therefore of utmost importance to understand better their properties, how they emerge, and how they can be controlled. In this talk, using perturbation theory we show that such inter-area modes generically occur in systems of coupled oscillators, even in large-scale well-connected graphs, and that they are triggered by any perturbation affecting either area. We finally discuss how to geographically distribute primary control to optimally damp them.

Localized states in coupled Cahn-Hilliard equations

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T. Frohoff-Hülsmann and U. Thiele

The classical passive Cahn-Hilliard model describes how a system characterized by a conserved order parameter field (e.g. concentration in a binary mixture) moves through phase decomposition towards equilibrium. In particular, any pattern of finite lengthscale is unstable w.r.t. coarsening. Here, we study an active two-field Cahn-Hilliard model that features a nonreciprocal coupling (maintaining both conservation laws). In contrast to other active Cahn-Hilliard-type models that describe phase separation in active systems, it exhibits a Turing (i.e. small-scale stationary) instability. In consequence, various stable patterns and localized structures exist. Employing numerical path continuation, we analyze the latter's snakes-and-ladders bifurcation behavior and as well discuss time-periodic localized states that replace the resting states at still larger activity.

Stability of a monostable front, after Turing bifurcation behind the front.

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Propagation fronts frequently appear in biology, and in reaction-diffusion equation. Whether they are stable or not is a natural question towards better understanding of such structures. Another phenomenon of interest is Turing bifurcation, that leads to the formation of periodic patterns when essential spectrum becomes unstable. Much work have been done about Turing bifurcation of bistable fronts. In this talk, I will present a similar situation with a KPP front, by working with a particular problem.

On the Approximation of Parameter-Dependent Attractors of Infinite-Dimensional Systems

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Recently, a novel set-oriented framework for the computation of finite-dimensional invariant sets of infinite-dimensional dynamical systems using embedding techniques has been developed. After briefly reviewing such methods we will introduce a one-dimensional parameter to the system and extend the subdivision scheme to a set-oriented path following method. Starting with an initial approximation for a fixed parameter value we will track the attractor with respect to the one-dimensional parameter. After presenting a simple method that uses a previously computed covering as the initial compact set, we will improve the algorithm and develop a predictor-corrector method. To this end, we will numerically realize a "set-valued" Taylor expansion that serves as a predictor step and modify the selection step in the subdivision algorithm as a corrector step. The feasibility of those tools will be illustrated on the Mackey-Glass delay differential equation where the parameter of interest is the time delay.

Resistive force theory and wave dynamics in swimming flagellar apparatus isolated from C. reinhardtii

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Cilia-driven motility and fluid transport are ubiquitous in nature and essential for many biological processes, including swimming of eukaryotic unicellular organisms, mucus transport in airway apparatus or fluid flow in the brain. The-biflagellated micro-swimmer Chlamydomonas reinhardtii is a model organism to study the dynamics of flagellar synchronization. Hydrodynamic interactions, intracellular mechanical coupling or cell body rocking is believed to play a crucial role in the synchronization of flagellar beating in green algae. Here, we use freely swimming intact flagellar apparatus isolated from a wall-less strain of Chlamydomonas to investigate wave dynamics. Our analysis on phase coordinates shows that when the frequency difference between the flagella is high (10–41% of the mean), neither mechanical coupling via basal body nor hydrodynamics interactions are strong enough to synchronize two flagella, indicating that the beating frequency is perhaps controlled internally by the cell. We also examined the validity of resistive force theory for a flagellar apparatus swimming freely in the vicinity of a substrate and found quantitative agreement between the experimental data and simulations with a drag anisotropy of ratio 2. Finally, using a simplified wave form, we investigated the influence of phase and frequency differences, intrinsic curvature and wave amplitude on the swimming trajectory of flagellar apparatus. Our analysis shows that by controlling the phase or frequency differences between two flagella, steering can occur.

Spatio-temporal representation of long delayed systems: a new perspective

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F. Marino and G. Giacomelli

Dynamical systems with long delay feedback can exhibit complicated temporal phenomena, which once re-organized in a two-dimensional space are reminiscent of spatio-temporal behavior. In this framework, normal forms description have been developed to reproduce the dynamics and the opportunity to treat the corresponding variables as true space and time has been since established. In this talk, we present an alternative approach with a different interpretation of the variables involved, which takes better into account their physical character and allows for an easier determination of the normal forms. We discuss such idea and apply it to a number of paradigmatic examples.

Structural polyhedral stability and pinning control of biochemical networks

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We consider biochemical systems associated with a generalised class of Petri nets with possibly negative token numbers. We show that the existence of a structural polyhedral Lyapunov function for the biochemical system is equivalent to the boundedness of the associated Petri net evolution or, equivalently, to the finiteness of the number of states reachable from each initial condition. For networks that do not admit a polyhedral Lyapunov function, we investigate whether it is possible to enforce polyhedral structural stability by applying a strong negative feedback on some specific pinned nodes: in terms of the Petri net, this is equivalent to turning pinned nodes into "black holes" that clear any positive or negative incoming token. If such nodes are chosen so that the transformed Petri net has bounded discrete trajectories, then there exists a stabilising pinning control: the biochemical network becomes Lyapunov stable if a sufficiently strong local negative feedback is applied to the pinned nodes. These results allow us to structurally identify the critical nodes to be locally controlled so as to ensure the stability of the whole network.

Paraxial fluids of light: from shockwaves to turbulence

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Reproducing the blast wind of an explosion in the laboratory or designing an experiment which mimics the physics just after the Big Bang on your optical table are not only exciting from an experimental perspective but also crucial on a fundamental level to test the universality of Physics laws at very different scales. This idea, initially raised by Feynman, triggered the development of analogue simulators.

In this talk we will present the recent progress of our platform for analogue simulation: paraxial fluids of light in a hot atomic vapor.

We will explain in details why light can be considered as a fluid and why this approach leads to a renewal of non-linear optics experiment in the field of shockwaves and turbulence. In particular, we will show two recent results. We will report the observation of two stream instabilities with light with the formation of vortices and snake instabilities during the collision of two counter-propagating photon fluids. And we will demonstrate the apparition of a negative relative pressure perturbation after a shock leading to a blast wind.

These two recent results open the way of studying turbulence and non-linear phenomena in fluids of light.

Collective meanfield dynamics of quadratic integrate-and-fire neurons beyond the Cauchy distribution

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D.S. Goldobin, M. di Volo and A. Torcini

The populations of quadratic integrate-and-fire neurons are known to form and maintain a Cauchy distribution of states of individual elements for several important network models (e.g., [PRX 5, 021028 (2015); PRL 121, 128301 (2018)]). One can show that these states are equivalent to the Ott-Antonsen ansatz in terms of phase variables. For an evolving Cauchy distribution, one can derive a low-dimensional equation system governing the dynamics of the mean membrane voltage and the firing rate. However, in some practically important setups, the Cauchy form of distribution (in other variables, the conditions of the applicability of the Ott-Antonsen ansatz) is distorted and the original low-dimensional model becomes inapplicable [PRL 121, 128301 (2018); PRE 100, 052211 (2019)]. We present an approach based on the characteristic function representation of the probability density deviating from the Cauchy distribution; for such a function ordinary cumulants diverge, but one can introduce alternative objects, 'pseudo-cumulants'. The real and imaginary parts of the first pseudo-cumulant are the firing rate and the mean voltage; higher pseudo-cumulants introduce small corrections to their dynamics. This description is not equivalent to the circular cumulant approach; the corrections due to the second circular cumulant coincide with those sue to the second pseudo-cumulant only to the first order of expansion with respect to a small parameter. Simultaneously, specifically for quadratic integrate-and-fire neuron populations, the pseudo-cumulant equation sets are much more concise than the circular cumulant ones and, more importantly, physical observables — mean voltage and firing rate — have a simple and natural representation in terms of pseudo-cumulants. The work was supported by the Russian Science Foundation (gr. #19-42-04120)

Data-driven methods for modeling and control in wound healing

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Predictive models can help bridge the gap between theory and biomedical applications. However, generating predictive models through a mechanistic approach remains a challenge due to limited observable states in a complex system. Biological systems are notoriously high dimensional and highly nonlinear. In this talk, we present efforts towards predictive modeling of wound healing for biological control. Wound healing involves a symphony of biological processes wherein the sequence and timing of said processes play a critical role in maintaining a normal healthy trajectory to wound closure. In order to make advances in wound healing it is important to identify candidate biomarkers as leverage points for intervention as well as arrive at a predictive model for wound healing stage. To this end, we introduce efforts towards data-driven methods for predictive models in wound healing in order to identify and drive systems towards desired reachable states. In addition, we propose the use of NN-based predictors and feedback controllers in order to direct cellular response to these states with no model a priori and no offline training required. The algorithms learn in real-time as information is received.

Self-organization of active particles with internal states

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Sheep, as many other biological systems, can be described as active particles with internal states. For this type of active particles, collective effects can result from i) interactions among active particles in the same states, as occurs in the Vicsek model via velocity alignment, or ii) by synchronizing of their internal state. Here, we discuss variety of collective patterns that emerge in these systems.

Active Particles in Vesicles and Cells

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T. Auth, D.A. Fedosov and G. Gompper

Active matter exhibits a wealth of emergent non-equilibrium behaviors [1-3]. A paradigmatic example is the interior of cells, where active cytoskeletal filaments are responsible for the structural organization and dynamics. Of particular interest is the interaction of active particles and filaments with membranes [4-8].

Vesicles (in three dimensions) [6] and closed polymer rings (in two-dimensions) [7,8] with internal active components can be considered as highly simplified models of cells. Here, the enclosed active particles and filaments lead to enhanced fluctuations [6,7] and an intimate coupling of propulsion forces, membrane deformability, cell shape, and restructuring in response to external perturbations [8]. The emerging self-organized cell shape and the motion characteristics are found to be tightly connected [8].

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Localized standing waves induced by spatiotemporal forcing.

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Particle-type solutions are observed in out of equilibrium systems. Depending on the states on which these localized solutions are constituted, different dynamic behaviors are observed. Based on a liquid crystal light valve with spatiotemporal modulated optical feedback, we investigate localized standing waves. These states correspond to a standing wave surrounded by another state. The bifurcation diagram is elucidated. Close to reorientation transition, an amplitude equation allows us to characterize the localized structures and establish their bifurcation diagram. In the high-frequency limit, we are establishing the origin of the localized states. Theoretical findings are in fair agreement with experimental observations.

Lyapunov Exponents for Transfer Operator Cocycles of Metastable Maps: a Quarantine Approach

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We investigate the Lyapunov-Oseledets spectrum of transfer operator cocycles associated to a class of random metastable maps, indexed by a parameter ϵ, quantifying the strength of the leakage between two nearly invariant regions. We show that the system exhibits metastability, and identify the second Lyapunov exponent λ_2^ϵ within an error of order $\epsilon^2|\log \epsilon|$. We show this approximation agrees with the naive prediction provided by a time-inhomogeneous two-state Markov chain. Furthermore, we show that $\lambda_1^\epsilon = 0$ and λ_2^ϵ are simple, and the only exceptional Lyapunov exponents of magnitude greater than $-\log 2 + O(\log\log \frac{1}{\epsilon} / \log \frac{1}{\epsilon})$.

Wave instability in the cell surface waves

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Dynamics within and between cells: from cell patterning to tissue adaptive responses

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A lot of animal and plant cell polarity can be understood by simple biochemical processes. Exploring their dynamics shows that simple "circuits" are able to generate a plethora of diverse cellular patterns. This core ability of a cell to polarize in isolation from others then leads to the collective emergence of tissue polarity, which will be dependent on the mode of cell-cell interaction. In plants, such tissue polarity will allow for information flow over large distances, be it to guide development or to interface the environment, such as in plant-nutrient uptake. We will show how for such organism-level coordination of signals, sub cellular components turn out to be extremely important. Also, we will discuss temporal-spatial dynamical constraints operating on such polarized tissues which are likely to have a evolutionary-developmental role in the systems we encounter in nature.

Generalized Hamiltonian Dynamics and Chaos in Evolutionary Games on Networks

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We study the network replicator equation and characterize its fixed points on arbitrary graph structures for 2×2 symmetric games. We show a relationship between the asymptotic behavior of the network replicator and the existence of an independent vertex set in the graph and also show that complex behavior cannot emerge in 2×2 games. This links a property of the dynamical system with a combinatorial graph property. We contrast this by showing that ordinary rock-paper-scissors (RPS) exhibits chaos on the 3-cycle and that on general graphs with ≥ 3 vertices the network replicator with RPS is a generalized Hamiltonian system. This stands in stark contrast to the established fact that RPS does not exhibit chaos in the standard replicator dynamics or the bimatrix replicator dynamics, which is equivalent to the network replicator on a graph with one edge and two vertices (K_2), but is consistent with past work showing a modified RPS game can exhibit chaotic behavior on K_2.

Reconfigurable intelligent surfaces within electromagnetic cavities : From wave chaos to applications.

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For decades, wave chaos has been an attractive field of fundamental research concerning a wide variety of physical systems such as quantum physics , room acoustics, microwave cavities ,etc. Its success is mainly due to its ability to describe such a variety of complex systems through a unique formalism, the so-called random matrix theory (RMT). More recently,chaotic cavities have been involved in a large variety of applications ranging from computational imaging to electromagnetic (EM) compatibility testing, as well as wavefront shaping for telecommunication. Traditionally cavities of elaborate geometries are used to implement a wave chaotic system. Recently, we have proposed a radically different paradigm: a cavity of regular geometry with tunable boundary conditions implemented through electronically Reconfigurable Intelligent Surfaces (RIS). The latter are able to locally control the phase shift on the reflected field. In a way, RIS are EM equivalent of Spatial Light Modulators used in optics or Schroeder's diffusers used in room acoustics.

I will first present a RMT model for reconfigurable cavities using RIS. This model is able to reproduce the experimentally observed behaviour of reconfigurable cavities and can help to design applications combining RIS and cavities. Then, I will present applications based on reconfigurable cavity. For example, RIS can be used to stir the EM field inside a cavity (as in a mode stirred reverberation chamber or in microwave oven). Thanks the tremendous stirring process with RIS, applications e.g. antenna characterization or EMC testing that rely on the statistical behavior of the field are more accurate. An other example of application, consists in partially removing a wall of a cavity feeded by a simple monopole antenna and use RIS in order to control how the field leak from the cavity. Such set-up can be used as beamformer for steerable flat panel antenna for SatCom or 6G applications.

Exact network modelling of theta oscillations in the hippocampal formation

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Theta oscillations are a prominent 4-10 Hz rhythm in the hippocampal field potentials, linked to memory processes. The origins of this rhythm remains elusive. In particular, it is not clear what is the role of each of the regions essential for in vivo hippocampal theta generation – the septum, hippocampus and entorhinal cortex (EC).

Recent experimental studies performed indicate that the EC may be the generator of theta rhythm in the hippocampal formation - not only is the EC leading the theta rhythm, but all hippocampal subregions are responding to a common rhythmic extrinsic input coming from the EC.

In this work, we propose a circuit model of the EC to study the intrinsic properties of the EC that allow for external excitatory inputs to drive the system into an oscillatory regime. We take advantage of a thermodynamic approach combined with an exact reduction method to get a simplified, exact description of the three major EC neural populations: stellate cells (SC), pyramidal cells (E), and fast-spiking interneurons (I). We start with the low-dimensional spiking model (Izikevich 2003) for each of the cell-type dynamic phenotypes and show how each of these can be exactly reduced to population activity equations. In order to study the contributions of the neural populations in the generation of the theta rhythm, we use a machine learning tools (Gonçalves et al. 2019) to infer the space of connectivity parameters that give rise to theta rhythmic activity in the EC network model. We provide analysis of the circuit dynamics. We found that theta generation is strongly constrained by the between the SC and E connectivity: a subnetwork of SC and E-cells can robustly generate synchronized theta oscillations. Our results clarify the roles of the cellular dynamics in the generation of the theta oscillations and of the importance for the hippocampal inputs for this process.

What is the mechanical basis of traveling waves of neural activity observed in motor cortex?

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Neural recordings display a variety of phenomena that require modeling the nonlinear dynamics of neural networks to be understood. Here, we focus on beta frequency (20Hz) oscillations that are observed in motor cortex during movement preparation. In several experiments, local field potentials (LFPs) recorded on separate electrodes of a multi-electrode array have been observed to display transient oscillations with non-zero phase shifts. They organize into a variety of traveling waves types. Beta oscillations have been successfully modeled as arising from reciprocal interactions between randomly connected excitatory (E) pyramidal cells and local inhibitory (I) interneurons. What accounts for transient bursts of beta oscillations and the observation of spatial waves has, however, remained unclear. Here, we use a rate model (mean-field) description of the local neural activity that has been shown in previous works to provide an accurate population level description of more detailed network simulations based on coupled spiking neurons. This offers the computational advantage that one can simulate and analyze large networks of local E-I modules with distance-dependent interactions and delays, matching those reported in previous experimental works. We study this model in a two-dimensional context. Stochastic local entries that vary on a long-time scale (200ms) are introduced to mimic inputs to the motor cortex from other neural areas. We compare our simulation results to electrophysiological datasets recorded in motor cortex of macaque monkey during an instructed delayed reach-to-grasp task. We find that our model closely agrees with the recordings. It reproduces the observed power spectrum of the local field potential, produces a variety of traveling waves of speed and types similar to those seen in experiments. Our results suggest that both time-varying external entries and intrinsic network architecture shape the LFP dynamics of motor cortex.

Theory of feature selectivity in rodent primary visual cortex

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The connectivity principles underlying the emergence of orientation selectivity in the primary visual cortex (V1) of mammals lacking an orientation map (such as rodents and lagomorphs) are poorly understood. We present a computational model in which random connectivity gives rise to orientation selectivity that matches experimental observations. The model predicts that mouse V1 neurons should exhibit intricate receptive fields in the two-dimensional spatial frequency domain, causing a shift in orientation preferences with spatial frequency. We find evidence for these features in mouse V1 using calcium imaging and intracellular whole-cell recordings.

Oscillations and waves of NADH subpopulations during glycolysis in yeast cells

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The energy metabolism of yeast cells presents a variety of states, depending on the energy load of the cell, and external conditions. Among the different states, oscillations of glycolysis and fermentation occur in starved, anaerobic yeast cells oscillations. Oscillatory dynamics of individual cells persists even when collective oscillations at the population levels cease. Therefore, glycolysis in yeast cells are well suitable model system for the study synchronisation.

The metabolic dynamics in yeast cells are monitored by measuring the endogenous fluorescence intensity of the intermediate NADH. We present a flurorescence lifetime study, which shows that cytosolic NADH (which from spectroscopic signals forms a single population) form distinctive subpopulations, which can be identified according to their lifetimes. The temporal and spatial dynamics of these subpopulations of NADH are studied during different metabolic states of yeast cell populations of high density.

Clustering of Inertial Particles in Turbulent Flow Through a Face-Centered Cubic Cell

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Fine inertial particle migration, transport and deposition is of importance in several applications such as hyporheic exchange of river beds, gravel packs in enhanced oil recovery, among others. Specifically, how turbulence within confined geometries of a porous bed affects migration, clustering, and deposition of fine particles is of importance. Direct numerical simulation is performed to investigate effect of turbulent flow in a face centered cubic porous unit cell on the transport of inertial particles at different Stokes numbers ($St_p = 0.01, 0.1, 0.5, 1$, and 2) and at a pore Reynolds number of 500. Particles are advanced using one-way coupling and collision of particles with pore walls is modeled as perfectly elastic specular reflection. The pattern of clustering is investigated using multiscale wavelet analysis and volume statistics of Voronoi tessellation cells. The results are compared with preferential concentration in forced isotropic turbulence to investigate the effect of geometric confinement on particle clustering. It is shown that the general features of cluster and void formation and higher order statistics of number density of particles are modified by the wall collision creating very fine scale clusters.

Experiments on Extreme Wave Events in the Vicinity of Reflective Beaches

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Wave hydrodynamics in coastal zones are known to comprise incident and reflective wave motion. It is also well-known that extreme events can arise in such complex wave states. We report an experimental study in which several incident JONSWAP wave trains have been generated in a uni-directional water wave tank while the artificial beach inclination and permeability have been varied to allow several reflective wave conditions. Key statistical features obtained from an adaptive coupled nonlinear Schrödinger model simulations show an excellent agreement with the laboratory data collected near the beach.

Transient chaotic dimensionality expansion by recurrent networks

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Cortical neurons communicate with spikes, which are discrete events in time. Even if the timings of the individual events are strongly chaotic (microscopic chaos), the rate of events might still be non-chaotic or at the edge of what is known as rate chaos. Such edge-of-chaos dynamics are beneficial to the computational power of neuronal networks. We analyze both types of chaotic dynamics in densely connected networks of asynchronous binary neurons, by developing and applying a model-independent field theory for neuronal networks. We find a strongly size-dependent transition to microscopic chaos. We then expose the conceptual difficulty at the heart of the definition of rate chaos, identify two reasonable definitions, and show that for neither of them the binary network dynamics crosses a transition to rate chaos. The analysis of diverging trajectories in chaotic networks also allows us to study classification of linearly non-separable classes of stimuli in a reservoir computing approach. We show that microscopic chaos rapidly expands the dimensionality of the representation while, crucially, the number of dimensions corrupted by noise lags behind. This translates to a transient peak in the networks' classification performance even deeply in the chaotic regime, challenging the view that computational performance is always optimal near the edge of chaos. This is a general effect in high dimensional chaotic systems, and not specific to binary networks: We also demonstrate it in a continuous 'rate' network, a spiking LIF network, and an LSTM network. For binary and LIF networks, classification performance peaks rapidly within one activation per participating neuron, demonstrating fast event-based computation that may be exploited by biological neural systems, for which we propose testable predictions.

Model Reductions and Coarse Graining in Controlled Oscillator Networks

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I discuss the reduction and aggregation of oscillators, specifically in the context of power grids. These reductions have to work when coupling is not small, but can rely on the system being designed to achieve certain control goals. A central challenge is to obtain parameters for the reduced descriptions from measurement data when latent, unobservable variables are present. I then discuss how control methods can be adapted using probablistic approaches to coarse grain such a system of oscillators.

Gait transition induced by hydrodynamic sensory feedback and central pattern generators in an anguilliform swimming robot

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Combining robotic experiments and synchronization theory, we report an investigation clarifying the mechanism behind the gait selection induced by hydrodynamical sensory feedback implemented in a anguilliform swimming robot. The actuation of the robot is controlled by an oscillators chains, where the oscillators are locally coupled and modulated by the amplitude of the hydrodynamical forces. When this amplitude reaches a threshold, the hydrodynamical sensory feedback entrain a travelling wave in the network of oscillators. This wave appears thought a bifurcation leading to a gait transition, such that the robot switches from an oscillating to an undulatory gait. By assuming that the sensory feedback produced a frequency detuning at leading order, we can compute the synchronized state with a very good agreement with the experimental data. To account for the bifurcation, we introduce a scenario based on a global odd mode breaking simultaneously the symmetry of the network and the body motion.

Data-driven modeling of cardiac dynamics by means of neural network hybrids

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The mechanical contraction of the pumping heart is driven by electrical excitation waves running across the heart muscle due to the excitable electrophysiology of heart cells. With cardiac arrhythmias these waves turn into stable or chaotic spiral waves whose observation in the heart is very challenging. Data-driven methods based on neural network hybrids consisting of convolutional neural networks for reconstructing and forecasting these spiral waves are presented. The performance our approach is demonstrated using the four variables of the Bueno-Orovio-Fenton-Cherry model describing electrical excitation waves in cardiac tissue.

Bayesian on-line anticipation of critical transitions

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Sudden transition events at so-called tipping points play an important role in a wide range of dynamical systems as in predator-prey dynamics, laser-physics, power systems, and are suspected to take part in systems of medicine, climate research and psychology and much more. The idea to predict these sudden and sometimes catastrophic transition events is a fascinating and useful task and lots of effort is done so far to find suitable leading indicators of such tipping events. Commonly known are leading indicator candidates as the autocorrelation at lag-1, the empirical standard deviation, the skewness and the kurtosis of a time series. In this talk another method is proposed based on MCMC and Bayesian probability analysis. The method is able to anticipate bifurcation-induced transitions, gives an estimate of the most probable transition time based on the current information and tracks the noise level at the same time. The on-line interpretation of an uprising indicator trend is facilitated by credibility bands. Furthermore, the analysis of two synthetic models implies a rather high robustness against noise compared with the above mentioned leading indicator candidates. The introduced method could turn out to be a useful alternative to existing anticipation procedures.

Isochrons, Phase Response and Synchronization Dynamics of Optically Injected Lasers

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Optically Injected Lasers (OIL) are widely applied and technologically relevant forced nonlinear oscillators that have been studied, both theoretically and experimentally, for more than three decades. They are well known for a remarkably rich set of complex dynamical features including different types of instabilities, cascades of bifurcations, multistability, as well as chaotic transitions [1]. Among them, the existence of stable limit cycles (LC) has the most fundamental role in terms of their practical applications as tunable photonic oscillators. In this work, we study the dynamical response of an OIL, operating at parameter values where such stable LC exist, in terms of the asymptotic phase of each initial condition that uniquely partitions the basin of attraction in a family of curves, known as isochrons in the literature of biological oscillators [2]. For the first time, the isochrons of characteristic LC of an OIL are numerically calculated, with the utilization of advanced techniques based on the Koopman operator formalism [3]. The complex structure of the isochrons in the phase space is systematically studied along with its dependence on coexisting dynamical objects related to the phaseless sets of the system and is shown to determine the Phase Response Curves (PRC) of the system under external perturbations as well as its synchronization characteristics [2]. The latter are studied in terms of a reduced single-dimensional Poincare map based on the PRC, and conditions for stable synchronization under parameter modulations are obtained.

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Extreme outbreak dynamics

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The COVID-19 pandemic has demonstrated how disruptive emergent disease outbreaks can be to societies. Classic modeling strategies for outbreak dynamics rely on either deterministic descriptions in which large outbreaks follow a single (mean-field) path that ends in a precise fraction of the population infected, or on stochastic branching processes that determine the likelihoods for small outbreaks of ininfinitesimal fractions. But what about the full range of outcomes, including extreme cases where the entire population eventually becomes infected? How do they occur and how likely are they to occur? In this talk, we develop an analytical large-deviations approach to calculate the dynamics and probabilities of such extreme outbreaks in populations of fixed size within the context of the canonical Susceptible-Exposed-Infected-Recovered model and more general COVID-19 models. In addition to providing a closed-form expression for the probability on log scale for all extreme outbreaks, we show that each outbreak entails a unique, constant depletion or boost in the pool of susceptibles and a constant increase or decrease in the effective recovery rate compared to the mean-field dynamics, due to finite-size noise. Moreover, unlike other kinds of rare-event processes in discrete stochastic particle systems, the underlying outbreak distribution depends on a full continuum of most-likely outbreak paths, each connecting two unique non-trivial fixed-points, and thus represents a novel class of extreme stochastic dynamics.

Directed percolation transition to turbulence

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Directed percolation has recently emerged as the likely solution to the century old riddle surrounding the onset of turbulence in simple shear flows. In pipes and ducts turbulence typically arises even though the laminar base flow is linearly stable. The resulting large scale flow patterns are characterized by the co-existence and the competition between laminar and turbulent domains. Although analogies between the dynamics of laminar turbulent fronts and directed percolation have already been proposed more than 30 years ago subsequent studies observed a discontinuous, non-universal scenario instead. I will here present a series of recent experiments that for the first time provide access to the excessive spatial and temporal scales that are relevant at the onset of turbulence and can hence clarify the nature of the transition.

Localized States in Passive and Active Phase-Field-Crystal Models

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The passive conserved Swift-Hohenberg equation (or phase-field-crystal [PFC] model) corresponds to a gra- dient dynamics for a single order parameter field related to density. It provides a simple microscopic description of the thermodynamic 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. Here we first discuss the snaking behavior of two coupled passive PFC equations, described by a common gradient dynamics. In two further steps this gradient dynamics is broken via (i) a non-reciprocal coupling and (ii) by replacing one of the passive PFC equations with an active PFC equation. In both cases we will analyze the influence of the nonvariational terms on the snakes-and-ladders structure employing numerical path continuation.

Rethinking the Definition of Rate-Induced Tipping

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Qualitatively, rate-induced tipping is often described as a critical transition in a system caused by the rate at which a parameter is changing. The current working definition of rate-induced tipping as a phenomenon in an nonautonomous differential equation is tied to the idea of a pullback attractor limiting in forward and backward time to a stable quasi-static equilibrium, called endpoint-tracking. We currently say that if a system has endpoint tracking, then it does not have rate-induced tipping. However, this definition is based on the assumption that the time-dependent parameter that induces the tipping is asymptotically constant in the limit as $t \to \pm\infty$. In this talk, I will show an example of a system in which the time-dependent parameter is not asymptotically constant, which is not endpoint tracking for any value of the rate parameter and which does not go through a critical transition. Additionally, I will show an example which is not endpoint tracking for any value of the rate parameter but does go through a critical transition that should be considered tipping. Based on this, we will consider an alternative definition that is equivalent to the current definition for asymptotically constant scalar systems and includes previously excluded N-dimensional systems that exhibit rate-dependent critical transitions.

Order–disorder transitions in a minimal model of active elasticity

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We introduce a new minimal model for self-propelled agents that attract, repel, and align to their neighbors through elastic interactions. This model has a simple mechanical realization and provides an approximate description of real-world systems ranging from active cell membranes to robotic or animal groups with predictive capabilities. The agents are connected to their neighbors by linear springs attached at a distance R in front of their centers of rotation. For small R, the elastic interactions mainly produce attraction-repulsion forces between agents; for large R, they mainly produce alignment. We show that the agents self-organize into collective motion through an order-disorder noise-induced transition that is discontinuous for small R and continuous for large R in finite-size systems. In large-scale systems, only the discontinuous transition will survive, as long-range order decays for intermediate noise values. This is consistent with previous results where collective motion is driven either by attraction-repulsion or by alignment forces. For large R values and different parameter settings, the system displays a novel transition to a state of quenched disorder. In this regime, lines of opposing forces are formed that separate domains with different orientations and are stabilized by noise, producing locally ordered yet globally disordered quenched states.

Coherence resonance in Erdös-Rényi networks describes the induction of cortical gamma activity

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Additive noise is known to tune the stability of nonlinear systems. Considering two randomly connected interacting excitatory and inhibitory neural Erdös-Rényi networks driven by additive noise, we derive a closed mean-field representation that captures the global network dynamics. Building on the spectral properties of the Erdös-Rényi networks, mean-field dynamics are obtained via a projection of the network dynamics onto the random network's principal eigenmode. We consider Gaussian zero-mean and Poisson noise stimuli to excitatory neurons and show that these noise types induce coherence resonance. Specifically, the stochastic stimulation induces coherent stochastic oscillations in the gamma-frequency range at intermediate noise intensity. We further show that this is valid for both global stimulation and partial stimulation, i.e. whenever a subset of excitatory neurons is stimulated only. The mean-field dynamics exposes the coherence resonance dynamics by a transition from a stable non-oscillatory equilibrium to an oscillatory equilibrium via a saddle-node bifurcation. Hence the noise-induced gamma activity represents a quasi-cycle. More detailed analysis indicates that medical drugs, such as ketamine and propofol, induce enhanced gamma-activity. This has been found in experimental brain data. We evaluate the transition between non-coherent and coherent state by power spectra, spike-field coherence and information-theoretic measures.

fractal dimensions and slow-fast systems

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In our talk we present a fractal analysis of canard cycles and slow-fast Hopf points in 2-dimensional singular perturbation problems under very general conditions. Our focus is on the orientable case and the non-orientable case. Given a slow-fast system, we generate a sequence of real numbers using the so-called slow relation function and compute a fractal dimension of that sequence. Then the value of the fractal dimension enables us to determine the cyclicity and bifurcations of canard cycles in the slow-fast system. We compute the fractal dimension of a slow-fast Hopf point depending on its codimension. Our focus is on the box dimension, one-sided dimensions and the fractal zeta-function. We also find explicit fractal formulas of Cahen-type for the computation of the above fractal dimensions and use them to detect numerically the number of canard limit cycles.

Ergoregion instabilities in rotating two-dimensional Bose-Einstein condensates: Perspectives on the stability of quantized vortices

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We investigate the stability of vortices in two-dimensional Bose–Einstein condensates. In analogy with rotating space-times and with a careful account of boundary conditions, we show that the dynamical instability of multiply quantized vortices in trapped condensates persists in untrapped, spatially homogeneous geometries and has an ergoregion nature with some modification due to the peculiar dispersion of Bogoliubov sound. Our results open perspectives to the physics of vortices in trapped condensates, where multiply quantized vortices can be stabilized by interference effects and singly charged vortices can become unstable in suitably designed trap potentials. We show how superradiant scattering can be observed also in the short-time dynamics of dynamically unstable systems, providing an alternative point of view on dynamical (in)stability phenomena in spatially finite systems.

Motion of the source and insert particles driven by the surface tension gradient and lateral capillary interaction

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In nonequilibrium conditions, a particle can move spontaneously consuming free energy, which is often called a "self-propelled particle". Here we focus on chemotactic self-propelled particles, which exhibit a directional motion in response to spatial gradients in the concentration field of chemical compounds. Although many studies have focused on the group of identical self-propelled particles, the actual systems in nature often include multiple types of self-propelled particles and/or passive particles, and therefore the understanding of the systems including multiple types of particles is awaited. In this study, we construct an experimental system in which a pair of source and inert particles is driven by surface tension gradient and attractive lateral capillary force. The source particle spreads the surface-active molecules around itself and is driven by the surface tension gradient due to the inhomogeneous concentration field. The inert particle is also driven by the surface tension gradient, though it does not affect the concentration field. In the present system, we used a camphor disk as the source particle. It is known that the camphor disk is driven by a concentration field through the surface tension gradient. As for the inert particle we used a metal washer. It can float at the aqueous surface by choosing the appropriate weight. In the actual experimental systems, an attractive lateral capillary force is exerted between them through the distortion of the aqueous surface. As a result, they got close to each other and then started motion. They exhibited straight and circular motions for the higher and lower PEG concentrations, respectively. Numerical calculations using a model that takes into account the forces due to the surface tension gradient, the lateral capillary force, and the effect of the excluded volume of the particles show that the change in the motion of the pair can be discussed from the viewpoint of the bifurcation theory.

A PDE model for unidirectional flows: stationary profiles and asymptotic behaviour

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In this work, we investigate the stationary profiles of a convection-diffusion model for unidirectional pedestrian flows in domains with a single entrance and exit. The inflow and outflow conditions at both the entrance and exit as well as the shape of the domain have a strong influence on the structure of stationary profiles, in particular on the formation of boundary layers. We are able to relate the location and shape of these layers to the inflow and outflow conditions as well as the shape of the domain using geometric singular perturbation theory. Furthermore, we confirm and exemplify our analytical results by means of computational experiments.

Decision making based on mode competition dynamics in a multimode semiconductor laser with optical feedback

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Photonic computing has been investigated intensively to overcome the limitation of the growth of semiconductor technologies in the post Moore era. One of the photonic computing techniques is known as photonic decision making to solve the multi-armed bandit problem [1]. For the multi-armed bandit problem, a player maximizes the total rewards by selecting repeatedly from multiple slot machines with unknown hit probabilities. A technique for solving the multi-armed bandit problem with two slot machines has been proposed using chaotic temporal waveforms of laser output [1]. A hierarchical architecture [2] and a method using a laser network [3] have also been proposed to solve the multi-armed bandit problem with more than two slot machines. However, these methods may cause difficulties of solving the multi-armed bandit problem depending on the arrangement of the slot machines. Therefore, it is important to introduce a new method for solving the multi-armed bandit problem with more than two slot machines. We focus on the nonlinear dynamics of multiple longitudinal modes in a multimode semiconductor laser with optical feedback. In multimode semiconductor lasers, mode competition dynamics occurs around the dominant mode with the largest laser output. We thus utilize the mode competition dynamics for solving the multi-armed bandit problem with more than two slot machines. We assign each slot machine to each longitudinal mode of the laser, and the slot machine corresponding to the dominant mode is selected during the mode competition dynamics. We found that we can achieve better performance of decision making using our proposed method than using a software algorithm, when the number of the slot machines is increased. This result suggests that multimode laser dynamics can accelerate the decision-making performance.

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Explosive synchronization in interlayer phase-shifted Kuramoto oscillators on multiplex networks

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We show that an introduction of a phase parameter with alpha in the interlayer coupling terms of multiplex networks of Kuramoto oscillators can induce explosive synchronization (ES) in the multiplexed layers. Along with the α values, the hysteresis width is determined by the interlayer coupling strength and the frequency mismatch between the mirror (inter-connected) nodes. A mean-field analysis is performed to support the numerical results. Similar to the earlier works, we find that the suppression of synchronization is accountable for the origin of ES. The robustness of ES against changes in the network topology and frequency distribution is tested. Different methods have been introduced in the past years to incite ES in coupled oscillators; our results indicate that a phase-shifted coupling can also be one such method to achieve ES. our results indicate that a phase-shifted coupling can also be one such method to achieve ES.

A normal form for rotating waves in oscillatory media with nonlocal interactions

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Biological and physical systems that can be classified as oscillatory media give rise to interesting phenomena like target patterns and spiral waves. The existence of these structures has been proven in the case of systems with local diffusive interactions. In this talk the more general case of oscillatory media with nonlocal coupling is considered. We model these systems using evolution equations where the nonlocal interactions are expressed via a diffusive convolution kernel, and prove the existence of rotating wave solutions for these systems. Since the nonlocal nature of the equations precludes the use of standard techniques from spatial dynamics, the method we use relies instead on a combination of a multiple-scales analysis and a construction similar to Lyapunov-Schmidt. This approach then allows us to derive a normal form, or reduced equation, that captures the leading order behavior of these solutions.

Modelling environmental-metabolic feedback in spatially distributed bio-films

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Biofilms are ubiquitous in medical settings. Biofilms can contain multiple distinct bacterial strains which complicate the task of tackling infections. Additionally, excretion of protective enzymes by bacteria within biofilms can inhibit the effects of anti-bacterials, providing regions wherein resistant strains may proliferate. It has been shown that within biofilms cross feeding between different cell types or species can support strains who would otherwise starve under substrate removal. These findings show that building a better understanding of biofilms and the dynamics within them will pay dividends in understanding bacterial infections. We seek to understand biofilm systems through mathematical modelling using our hybrid modelling platform ChemChaste. ChemChaste has been developed with the aim of modelling realistic chemical dynamics and the chemical interactions between cells via their microenvironment. Here, biofilms are modelled through coupling multiple reaction-diffusion systems to a population of individual cell agents. The cells each have their own metabolic models encoding different cell types. They can interact through the excretion and uptake of chemicals in the shared film environment. The spatial distribution of these cells and their behaviours is investigated under a range of metabolic processes and phenomena. Therein providing insights into the complex dynamics that may suggest clinical applications.

A Mathematical Model of Immunity and Tolerance of Disease

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When an organism is challenged with a novel pathogen a cascade of events unfolds. The innate immune system rapidly mounts a preliminary nonspecific defense, while the acquired immune system slowly develops microbe-killing specialists. These responses cause inflammation and collateral damage, which the anti-inflammatory mediators seek to temper. This interplay of counterbalances is credited for maintaining health, but it may produce unexpected results such as disease tolerance. This outcome is characterized by the persistence of pathogen with minimum deleterious effects to the host, who is often capable of spreading it to others. Tolerance is poorly understood, indicating a need for theoretical study. Accordingly, we present a novel differential equation model of infection and immunity derived from bulk fundamental interactions and demonstrate that it can produce clinically relevant health and death scenarios. Model simulation and numerical analysis show that these states are determined by pathogen virulence and the strength of the innate response to trauma. By exploring various regions of parameter space, we find that the immune system's reaction to tissue damage plays a significant role in disease tolerance, along with the longevity of active immune cells. Bifurcation theory corroborates these findings and displays a region between health and death in which host and pathogen vitals oscillate in the absence of medical intervention, suggesting that damage mitigation and delayed programmed cell death are key players in the maintenance of disease.

Rate-induced tipping and its relevance to climate change

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The climate is changing due to the heat trapping caused by the rapid increase in greenhouse gases, mainly carbon dioxide, in the atmosphere. One way to see the challenge we face is that we cannot, as a species, adapt to the new conditions quickly enough. The inability to continually adjust is what happens in rate-induced tipping. While climate tipping scenarios are mostly viewed in terms of bifurcation-based tipping or noise-induced tipping, it may be that rate-induced tipping is the most relevant because parameters effecting these shifts are changing more rapidly than the ability of the system to adjust. I will discuss the dynamical systems behind rate-induced tipping, which has been developed over the past ten years, open questions, applications to climate related systems and interesting new directions in which noise and rate change are working together. I will explain why the unifying dynamical systems theme is finding heteroclinic orbits.

Linear response for finite-time coherent sets from data

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Finite-time coherent sets represent minimally mixing objects in general nonlinear dynamics, and are spatially mobile features that are the most predictable in the medium term. When the dynamical system is subjected to small parameter change, one can ask about the rate of change of (i) the location and shape of the coherent sets, and (ii) the mixing properties (how much more or less mixing), with respect to the parameter. We answer these questions by developing linear response theory for the eigenfunctions of the dynamic Laplace operator, from which one readily obtains the linear response of the corresponding coherent sets. We construct efficient data based numerical methods and provide numerical examples.

Geometric singular perturbation analysis of the Hodgkin-Huxley equations

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In this work, we present a three-dimensional reduction of a modified version of the Hodgkin-Huxley equations [J. Rubin and M. Wechselberger, Biological cybernetics, 97 (2007)] that is based on geometric singular perturbation theory. We investigate the dynamics of this reduction in two distinct parameter regimes. We demonstrate that in the first regime, the system exhibits bifurcations of oscillatory dynamics and complex mixed-mode oscillations, in accordance with the geometric mechanism introduced in [P. Kaklamanos, N. Popovic, and K. U. Kristiansen, (2020)], while in the second regime, it displays characteristics of a slow-fast system in non-standard form. We relate our results to previous work [S. Doi et al., Biological cybernetics, 85 (2001)] where such dynamics in the corresponding regimes have been documented but the underlying geometry was not emphasised.

The granular monoclinal wave: a dynamical systems survey

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G. Kanellopoulos, D. Razis and K. van der Weele

The monoclinal wave, often encountered in river floods, is a nonlinear travelling shock structure connecting two flow regions (plateaus) with different depths. Its granular counterpart was first reported by our group in 2018 [1]. Very recently [2] we performed a dynamical systems survey of this waveform. Starting from the diffusive Saint-Venant equations for flowing granular matter, we extract a second-order ODE governing the shape of this waveform. It is found that the granular monoclinal wave manifests itself in phase space as a heteroclinic orbit connecting two fixed points: a saddle and an unstable node, representing a shallow and a deep plateau, respectively. By studying the local properties of these fixed points, it is revealed that if the trace of the Jacobian matrix calculated on the saddle is positive, then the monoclinal wave can be accurately described by the non-diffusive (first-order) approximation of the aforementioned ODE. This constitutes a significant simplification of the waveform dynamics, opening the road for several analytical results.

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EP-Net 2.0: Out-of-Domain Generalisation for Deep Learning Models of Cardiac Electrophysiology

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Cardiac electrophysiology models achieved good progress in simulating cardiac electrical activity. However, it is still challenging to leverage clinical measurements due to the discrepancy between idealised models and patient-specific conditions. In the last few years, data-driven machine learning methods have been actively used to learn dynamics and physical model parameters from data. In this paper, we propose a principled deep learning approach to learn the cardiac electrophysiology dynamics from data in the presence of scars in the cardiac tissue slab. We demonstrate that this technique is indeed able to reproduce the transmembrane potential dynamics in situations close to the training context. We then focus on evaluating the ability of the trained networks to generalize outside their training domain. We show experimentally that our model is able to generalize to new conditions including more complex scar geometries, multiple signal onsets and various conduction velocities.

Universal upper estimate for prediction errors under moderate model uncertainty

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We present a method of sensitivity analysis for general dynamical systems subjected to deterministic or stochastic modeling uncertainty. Using the properties of the unperturbed, idealized dynamics, we derive a universal bound for the leading-order prediction error. Specifically, our estimates give upper bounds on the leading order trajectory-uncertainty arising along model trajectories, solely as functions of the invariants of the known Cauchy-Green strain tensor of the idealized model. Our bounds turn out to be optimal, which means that they cannot be improved for general systems. This bound motivates the definition of the Model Sensitivity, a scalar quantity, depending on the initial condition and time. We use nonlinear numerical models of various complexities, we demonstrate that the Model Sensitivity provides both a global view over the phase space of the dynamical system and, in some situations, a localized, time-dependent predictor of uncertainties along trajectories. This is reflected by the fact that the mean-squared trajectory uncertainty qualitatively follows the leading-order bound for surprisingly long time intervals. In addition, we use energy balance type models of the climate system, to show that the method is expected to scale to models of higher dimension. We also find that the phase-space structure of the Model Sensitivity (MS) is related but not identical to that of the Finite-Time Lyapunov Exponents (FTLE).

Koopman operator and phase and amplitude functions for stochastic oscillators

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Y. Kato, J. Zhu and H. Nakao

The phase and amplitude are fundamental quantities for the analysis of deterministic limit-cycle oscillators. For stochastic oscillatory systems, Thomas and Lindner proposed a definition of the asymptotic phase in terms of the slowest decaying eigenfunction of the backward Kolmogorov (Fokker-Planck) operator describing the mean first passage time, which yields phase values that increase with a constant frequency on average for stochastic oscillations, in a similar way to the ordinary asymptotic phase for deterministic oscillators. In this talk, we show that this definition of the asymptotic phase for stochastic oscillators is a natural extension of the deterministic definition in the sense that it is given by the argument (polar angle) of the Koopman eigenfunction. On the basis of the Koopman eigenfunction, we also introduce the amplitude functions for stochastic oscillators. We show that the phase and amplitude functions give appropriate values in examples of a noisy Stuart-Landau oscillator and a noisy FitzHugh-Nagumo oscillator.

Parameter-robust decoupling and long-lasting desynchronization by Random Reset stimulation

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Excessive neuronal synchrony is a hallmark of several neurological disorders including Parkinson's disease (PD). In PD, permanent high-frequency deep brain (HF DBS) is used to suppress symptoms, however symptoms return shortly after cessation of stimulation. Random Reset (RR) is a novel stimulation method and it is designed to induce long-lasting desynchronization by specifically targeting the pathological connectivity [1,2]. In RR stimulation, the spatio-temporal randomized stimulus pattern is used to effectively decouple networks and push networks to stable desynchronized states. In our setup the temporal randomization is realized by allowing the inter-stimulus intervals to follow an exponential distribution, while the spatial randomization is realized by delivering stimuli simultaneously to L randomly selected stimulation sites out of a total of M stimulation sites, which will be called L/M-RR stimulation [2]. The spatial randomization is motivated by the recently developed segmented electrodes with multiple stimulation sites. We study the decoupling by L/M-RR stimulation in networks of excitatory leaky integrate-and-fire neurons with spike-timing dependent plasticity (STDP). We show that L/M-RR stimulation leads to parameter-robust decoupling and long-lasting desynchronization. Our theory reveals that strong high-frequency stimulation is less efficient for inducing long-lasting desynchronization effects. Remarkably, we find that L/M-RR stimulation does not rely on a high spatial resolution, characterized by the density of stimulation sites in a target area, corresponding to a large M. We show that L/M-RR stimulation with low resolution, i.e. delivered through only a few stimulation contacts, performs even better at low stimulation amplitudes. L/M-RR stimulation may present a way to exploit modern segmented lead electrodes for long-lasting therapeutic effects.

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The response of network dynamics to link modification

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A major issue in the study of complex network systems, such as neuroscience, ecological networks, and power grids, is to understand the response of network synchronization to link modifications. The local stability of the globally synchronized state depends on the spectral properties of the Laplacian matrix representing the network. Due to the asymmetry of the Laplacian matrix of a directed graph, adding directed links might cause a decrease in the real part of the second minimum eigenvalue of the Laplacian, and hence synchronization loss in the network. We consider a weakly connected directed graph consisting of two strongly connected components connected by a directed link (called cutset). We study the transitions to synchronization in such networks when a new directed link between the components, in the opposite direction of the cutset, is added to the network and makes the whole network strongly connected. We explore which properties of underlying graphs and their connected components may hinder the synchronization (i.e., decreasing in the real part of the second minimum eigenvalue of the Laplacian). We are aiming to find optimal strategies to modify networks to stabilize the synchronized solutions.

Double-diffusive instabilities in rotating hydrodynamic and magnetohydrynamic flows

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The Prandtl number, i.e. the ratio of the fluid viscosity to a diffusivity parameter of other physical nature such as thermal diffusivity or ohmic dissipation, plays a decisive part for the onset of instabilities in hydrodynamic and magnetohydrodynamic flows. The studies of many particular cases suggest a significant difference in stability criteria obtained for the Prandtl number equal to 1 from those for the Prandtl number deviating from 1. We demonstrate this for a circular Couette flow with a radial temperature gradient and for a differentially rotating viscous flow of electrically conducting incompressible fluid subject to an external azimuthal magnetic field. Furthermore, in the latter case we find that the local dispersion relation is governed by a pseudo-Hermitian matrix both in the case when the magnetic Prandtl number, Pm, is Pm=1 and in the case when Pm=-1. This implies that the complete neutral stability surface contains three Whitney umbrella singular points and two mutually orthogonal intervals of self-intersection. At these singularities the double-diffusive system reduces to a marginally stable G-Hamiltonian system. The role of double complex eigenvalues (exceptional points) stemming from the singular points in exchange of stability between modes is demonstrated.

Efficient reduction of the collective dynamics of neural populations with realistic forms of heterogeneity

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Reduction of collective dynamics of large heterogeneous populations to low-dimensional mean-field models is an important task of modern theoretical neuroscience. Such models can be derived from microscopic equations, for example with the help of Ott-Antonsen theory. An often used assumption of the Lorentzian distribution of the unit parameters makes the reduction especially efficient. However, the Lorentzian distribution is often implausible as having undefined moments, and the collective behavior of populations with other distributions needs to be studied. In the present Letter we propose a method which allows efficient reduction for an arbitrary distribution and show how it performs for the Gaussian distribution. We show that a reduced system for several macroscopic complex variables provides an accurate description of a population of thousands of neurons. Using this reduction technique we demonstrate that the population dynamics depends significantly on the form of its parameter distribution. In particular, the dynamics of populations with Lorentzian and Gaussian distributions with the same center and width differ drastically.

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Magnetotactic navigation in complex environments

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Magnetotatic bacteria, which align along magnetic field lines with the help of a linear chain of mag- netic organelles called magnetosomes, provide an example for magnetic active matter and an excellent model system to study the interplay of physical and biological processes. The combination of magnetic and aerotactic directionality, and their (steric and hydrodynamic) interactions with walls result in intriguing trajectories in complex environments. We will report on several studies addressing this interplay in a combination of experimental and theoretical approaches, specifically aerotactic band formation and their behavior in confined environments.

Spatially Adaptive Projective Integration for Moment Models of Rarefied Gases

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Moment models are successfully used to simulate rarefied gases. They are hyperbolic balance laws that can be stiff with several spectral gaps, especially if the relaxation time significantly varies throughout the spatial domain. We perform a detailed spectral analysis of the semi-discrete model that reveals the spectral gaps. Based on that, we show the inefficiency of standard time integration schemes expressed by a severe restriction of the CFL number. We then develop the first spatially adaptive projective integration schemes to overcome the prohibitive time step constraints of standard time integration schemes. The new schemes use different time integration methods in different parts of the computational domain, determined by the spatially varying value of the relaxation time. We use our analytical results to derive accurate stability bounds for the involved parameters and show that the severe time step constraint can be overcome. The new adaptive schemes can obtain a large speedup with respect to standard schemes.

Modeling liquid crystal films on nanoscale

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L. Kondic and L.J. Cummings

This talk will focus on recently developed models and computational techniques for thin films, with focus on nematic liquid crystal films. Models and computations are formulated within the framework of the long wave approach, augmented by the inclusion of nematic-solid interaction forces via disjoining pressure model. Particular aspects that will be discussed involve inclusion of liquid-crystalline nature in the model in a tractable manner. The resulting asymptotic model allows for discussing dewetting type of instabilities of nematic films and in particular the influence of nematic properties on the nature of dewetting. The second part of the talk will build upon the first one by considering explicitly anisotropic nature of the nematic films and the influence which such anisotropy has on dewetting. The analytical techniques are supplemented by large scale GPU based simulations that allow for computing in large domains and for discussion of various instability mechanisms in a fully nonlinear setting.

Reactive islands framework for systems with three degrees of freedom

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Transport between regions of phase space in Hamiltonian systems is governed by invariant geometric structures that act as separatrices between volumes of qualitatively different kinds of dynamics. At a fixed energy in systems with two degrees of freedom, these structures are stable and unstable manifolds asymptotic to unstable periodic orbits. Reactive island theory introduced by *Ozorio de Almeida et al.*, *Physica D 46 (1990)* has been successfull at providing insight into the qualitative and quantitative aspects of the structure of these manifolds. Many works that used reactive island theory stated the need to advance reactive islands to higher dimensional systems. This talk will present our recent work bringing reactive island theory to three degrees of freedom and discuss the approaches needed to investigate stable and unstable manifolds of normally hyperbolic invariant manifolds.

Effects of state-dependence in the delayed feedback loop driving El Niño

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We consider here a conceptual delay differential equation (DDE) model of delayed-action-oscillator type for the El Niño Southern Oscillation (ENSO) phenomenon, which refers to irregular and hard to predict warm seasons of the eastern equatorial Pacific Ocean about every 4-7 years. Traditionally, the delay of the main feedback loop is taken to be constant, which is a considerable modelling assumption. We present arguments for the state dependence of delays in the ENSO DDE model and then conduct a bifurcation analysis to investigate its effects on the observed dynamics of the system. More specifically, we show that the underlying delay-induced structure of resonance regions may change considerably in the presence of state dependence. More generally, this case study shows that state-dependence of delays is capable of generating entirely new dynamics, and that its effects can be studied effectively with the now available continuation tools.

Universal aspects and irreversibility of superfluid vortex reconnections

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Vortex reconnections in fluids have been object of study for long time in the context of both classical and superfluid dynamics. Such reconnections are events characterised by a rearrangement in the topology of the vorticity field. In superfluids, they have been observed experimentally and have been the subject of several theoretical studies over the last years.

In this talk I will present recent results on superfluid vortex reconnections based on numerical simulations and analytical calculations within the framework of the Gross-Pitaevskii model. The aim is to highlight what are the universal aspects of vortex reconnections. In particular, I will show that about the reconnection event, vortex lines alway approach and separate accordingly to the same temporal scaling with numerical pre-factors that depend on the vortex configuration. Despite the time reversibility of the model, we report clear evidence that the dynamics of the reconnection process is time irreversible, as reconnecting vortices tend to separate faster than they approach.

This time asymmetry is shown to be a consequence of the sound radiated during the reconnection process and can be analytically explained by a simple theory.

Geometric-mechanical coupling of chemical waves

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Cell migration is driven by a network of filamentous actin polymers that interact through a large number of associated proteins. How this so-called actin cytosekeleton is organised during migration is in many cases still unknown. This holds, in particular, for collective migration phenomena. Spontaneous actin polymerisation waves have been identified in a number of cells to provide a means for cytoskeletal organisation in single cells. When impinging on the cell boundary, these waves can deform the cell shape and thus provide directional cues for the migrating cell. Here, we study the coupling between actin waves in different contacting cells. We find that by inducing shape changes in adjacent cells, actin polymerisation waves can synchronise and lead to coherent motion of groups of cells.

Adaptive Epidemic Network Dynamics

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In this talk, I am going to provide a survey of several results obtained together with several colleagues during the last ten years on adaptive network models for epidemic dynamics with a reflection on recent developments triggered by the COVID-19 pandemic. The results include local bifurcations unfoldings, existence of periodic solutions, early-warning signs for transitions, as well as optimal balancing of quarantine and social distancing measures.

Self-organized patterning on the soft tubular structure

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Spatial gradients yield self-organized patterns in systems far from equilibrium. Here, we study the organized structures when an acidic solution of chitosan with various molecular weights is injected into a pool of sodium hydroxide solution. The compressive stress generates the surface instabilities on the boundary-aided tubules. Wrinkling and folding patterns are monitored by varying the flow rates and the container's orientation. The characteristic properties of the tubes support the physical features of the organized patterns. Furthermore, in the presence of metal salts, Liesegang-like micropatterning of precipitations have been explored. The flow-driven conditions provide a simple framework for designing pattern formations and control over the structures.

Widening the criteria for emergence of Turing patterns: no need for differential diffusivity and more

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In 1952 Alan Turing suggested that the key to many events of formation of organs in living organisms may be the instability of a spatially uniform state in a system of chemicals, which diffuse throughout the tissue, interact with each other and locally affect the behavior of cells. Nowadays, the widely-used concept for the emergence of stationary Turing patterns in mathematical models is the requirement that the considered model system should be composed of complementary sufficiently slowly diffusing unstable subsystem and sufficiently rapidly diffusing stable subsystem. According to this concept, Turing patterns can arise in a significant range of kinetic parameters only if the mobilities of the variables differ significantly, which is a quite rigid restriction for biological systems. In this talk an extension of the concept for emergence of Turing patterns in multicomponent systems will be provided. In particular, it will be shown, that under the presence of one immobile element, which does not directly affect its own production, and under certain set of types of interactions between this element and mobile elements, Turing structures should form spontaneously under any values of mobilities of the mobile elements and under any values of kinetic parameters of the system, at least if it is stable in the absence of diffusion. Such conditions offer a more complex, but much more robust mechanism for the emergence of Turing patterns compared to the classical one.

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Observation of sound emission and annihilation in a quantum vortex collider

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Vortex dynamics lies at the heart of understanding quantum fluids. Dissipation of the energy of quantized vortices constitutes a central concept in describing quantum hydrodynamics, such as superfluid turbulence and its decay. Typical quantum vortex dissipation mechanisms are friction occurring via interaction with normal components and phonon emissions due to vortex-sound interaction. However, the scarcity of clean experimental tools plays a part in limiting deep understanding of vortex-sound interaction. Here, we realize a deterministic, programmable quantum vortex collider in atomic Fermi superfluids and directly observe sound-mediated dissipation and its ultimate form, i.e., vortex annihilation. We further find that fermionic quasiparticles bounded in a vortex core could take a significant role in vortex energy dissipation, possibly signaling additional dissipation mechanism other than sound emission.

Dynamics of coupled Kuramoto oscillators with distributed delays

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A. Ross, S.N. Kyrychko, K.B. Blyuss and Y.N. Kyrychko

In this talk I will discuss the effects of two different types of delay-distributed coupling in the system of two mutually coupled Kuramoto oscillators, one where the delay distribution is considered inside the coupling function, and another where the distribution enters outside the coupling function. In both cases, the existence and stability of phase-locked solutions will be analysed for uniform and gamma distribution kernels. The results indicate that while having distribution inside the sine function only changes parameter regions where phase-locked solutions exist, when the distribution is taken outside the sine function, it affects both the existence, as well as stability properties of in- and anti-phase states. For both distribution types, various branches of phase-locked solutions are computed, and regions of their stability are identified for uniform, weak and strong gamma distributions [1].

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Instability windows of Chandrasekhar-Friedman-Schutz instability

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J. Labarbe and O.N. Kirillov

Rotating, self-gravitating mass of incompressible ideal fluid possesses an axially symmetric equilibrium configuration known as the Maclaurin spheroid. Fluid viscosity causes dissipation-induced instability of this equilibrium. Chandrasekhar discovered that radiation reaction force due to emission of gravitational waves could lead to a radiative instability of the Maclaurin spheroids. In the presence of both viscosity and resistivity, the ratio of these two dissipative forces plays a crucial role, determining the instability window for the Chandrasekhar-Friedman-Schutz (CFS) instability. The CFS instability is commonly accepted nowadays as one of the main triggers of gravitational radiation from single neutron stars that is the next goal for the existing (LIGO, Virgo) and planned (LISA) detectors of gravitational waves. Perturbation theory for eigenvalues in combination with numerical methods was proposed for calculation of instability windows of the CFS instability already in previous works. We are extending this approach to the multiple-parameter case by adopting established methodology to get better approximations and to put the CFS to the general context of the dissipation-induced instability theory.

Master stability functions & pattern formation: from networks to continua

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Large networks are becoming increasingly prominent in many areas such as physics, applied mathematics, and mathematical biology. The often data-driven analysis of such large networks can yield great insight but also pose new computational challenges. One way to sidestep this is to attempt to understand the behaviour of the continuum limits of such networks, both as generative models for large random graphs as well as standalone mathematical objects. Here, we combine recent work on one such limit - the graphon - with Master Stability Function analysis, a powerful tool for studying the stability of synchronous oscillatory or chaotic states in coupled dynamical systems. In doing so, our network dynamical system is converted into a nonlocal partial differential equation (PDE), where the connectivity matrix is replaced by an integral operator with a graphon kernel. One important example application of this framework is that it yields a natural method to derive a neural field model from a network of neurons. Furthermore, we find that this method can also be applied more generally than graphon integral operators, such as reaction-diffusion PDEs. Here the framework allows us to perform Turing pattern-like analysis around a spatially homogeneous oscillatory state (instead of a steady state). The generality of the method allows for straightforward construction of extensions, e.g. anisotropic & fractional diffusion.

Effects of degree distributions in random networks of type-I neurons

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We consider large networks of theta neurons and use the Ott/Antonsen ansatz to derive degree-based mean field equations governing the expected dynamics of the networks. Assuming random connectivity we investigate the effects of varying the widths of the in- and out-degree distributions on the dynamics of excitatory or inhibitory synaptically coupled networks, and gap junction coupled networks. For synaptically coupled networks, the dynamics are independent of the out-degree distribution. Broadening the in-degree distribution destroys oscillations in inhibitory networks and decreases the range of bistability in excitatory networks. For gap junction coupled neurons, broadening the degree distribution varies the values of parameters at which there is an onset of collective oscillations. Many of the results are shown to also occur in networks of more realistic neurons.

Existence and uniqueness of solutions for stochastic shallow water models driven by transport noise

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O. Lang and D. Crisan

In this talk I will describe the analytical properties of two stochastic rotating shallow water models. One of these models is derived using the Location Uncertainty approach (Mémin, 2014) and the other one is derived using the Stochastic Advection by Lie Transport method (Holm, 2015). Both systems are designed for turbulent compressible fluids and are driven by transport noise. Our methodology is based on approximating sequences of solutions with suitable convergence properties, and can be extended to more general systems of SPDEs.

Mean field limit of Ensemble Square Root Filters

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T. Lange and W. Stannat

In many applications in the geosciences, one is interested in determining the current state of an unknown dynamical system given noisy observations. This involves identifying the conditional distribution of the system conditioned on all observations up until current time, and numerical experiments showed that in various cases it suffices to know only the conditional mean m and the conditional covariance matrix Σ. Ensemble Square Root Filters form a class of algorithms inspired by the Kalman Filter which approximate m and Σ by first and second empirical moment of a finite-size ensemble, hence in order to investigate their approximation skills I will present recent results on their asymptotic behaviour as the ensemble size M increases. This is joint work with Wilhelm Stannat in which both in discrete and continuous time, we identified limiting mean field processes on the level of ensemble members, proved propagation of chaos results and derived associated convergence rates in terms of M.

Dynamics of a vortex lattice in a nonequilibrium polariton superfluid

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If a quantum fluid is driven with enough angular momentum, at equilibrium the ground state of the system is given by a lattice of quantised vortices whose density is prescribed by the quantization of circulation. We report on the first experimental study of the Feynman-Onsager relation in a non-equilibrium polariton fluid, free to expand and rotate. We imprint a lattice of vortices in the quantum fluid, and track the vortex core positions. We observe an accelerated stretching of the lattice and an outward bending of the linear trajectories of the vortices, due to the repulsive polariton interactions. We detect a small deviation from the Feynman-Onsager rule in terms of a transverse velocity component, due to the density gradient of the fluid envelope acting on the vortex lattice.

Chaotic dynamics in an optical lattice

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Spatial diffusion of particles in periodic potential models has provided a good framework for studies on the role of chaos in global properties of classical systems in cases where ergodic-like motion occurs without the application of random forces, occurring purely due to dynamical instabilities. Here a 2D 'soft' billiard, classically modeled from an optical lattice hamiltonian system, was used to study diffusion transitions taking place with the variation of its main control parameters. Sudden transitions between normal and ballistic regimes were found and characterized by inspection of the topological changes undergoing in its phase-space. Few of these transitions correlate with changes in the chaotic area, given the onset of island myriads for transitions where local maxima points induce further instabilities in the system and a slow-down of the dynamics.

Evolving epileptic brain networks

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Epilepsy is one of the most common serious neurological disorders, affecting approximately 65 million people worldwide. Epileptic seizures are the cardinal symptom of this multi-facetted disease and are usually characterized by an overly synchronized firing of neurons. Seizures cannot be controlled by any available therapy in about 25% of individuals, and knowledge about mechanisms underlying generation, spread, an termination of the extreme event ”seizure” in humans is still fragmentary. Epilepsy is nowadays conceptualized as a network disease with functionally and/or structurally aberrant connections on virtually all spatial scales. All constituents of large-scale epileptic networks can contribute to the generation, maintenance, spread, and termination of even focal seizures as well as to the many pathophysiologic phenomena seen during the seizure-free interval. I will provide a brief overview of the progress that has been made in understanding the long-term dynamics of large-scale epileptic networks and will discuss recent investigations into network-based mechanisms of seizure generation.

Searching for intermittent processes in stochastic eye-gaze trajectories

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The interest in intermittent spatial processes is driven by its ability to describe search strategies such as animal foraging and intracellular transport [1]. The criteria for the optimization of intermittent processes as a search strategy have been identified and a remarkable correspondence between experimental data and theoretical model has been observed [2]. To extract the parameters from an in situ recorded intermittent trajectory we should be able to separate the different regimes that compose it, namely localized diffusive-like events and near-ballistic relocations [3]. This is not a trivial task, taking into account that the two alternating phases are not ‘ideal’ (e.g. ballistic relocations are not straight lines and may have varying velocity). We present an overview of the currently used algorithms and address how to overcome some of the present challenges to uncover the parameters characterizing an intermittent process. We focus on the specific case of eye-gaze trajectories.

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Parametrcially driven dissipative optical solitons

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Dissipative solitons in Kerr cavities have been attracting a lot of attention this past decade. They have shown promise for many applications such as ranging, computing, data transmission as well as microwave generation. In this talk, I will introduce parametrically driven Kerr solitons. I will show how Kerr cavity solitons can be excited at twice their carrier frequency and discuss the advantages of such parametric solitons over their externally driven counterparts. In particular, I will discuss how their multiplicity extends the application pool of Kerr solitons to Ising machines and random number generation.

Active glass & polycrystal: ergodicity breaking dramatically affects response to self-propulsion

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We study experimentally a sediment of self-propelled Brownian particles with densities ranging from dilute to ergodic supercooled to nonergodic glass, to nonergodic polycrystal. We observe a dramatic slowdown of relaxation of nonergodic states when particles become weakly self-propelled. By contrast, ergodic supercooled states always relax faster with self-propulsion. Our system is a monolayer of micron-size gold-platinum Janus particles, which become active upon adding a solution of hydrogen peroxide due to self-phoretic propulsion mechanisms. We characterise the activity level in our system with an effective temperature defined from the density profile. Standard glassy physics describes well the ergodic regime provided the replacement of the ambient temperature by this effective temperature: higher temperature implies faster relaxation. However beyond the glass transition, the relaxation of the nonergodic system abruptly slows down at low but nonzero activity. As we increase further activity, the relaxation speeds up until it exceeds the passive situation. This nonmonotonic behavior cannot be described by a simple increase in temperature. The same nonmonotonic response is observed in polycrystal. To explain this phenomenon, we correlated particle displacement orientation and calculated the average length of correlated domains. This length is inversely correlated with relaxation times, with small lengths corresponding to slow relaxation. This suggests that relaxation in sufficiently active nonergodic phase follows collective motion mechanisms, while cooperative motion dominates at zero and low activities. We propose that directed motion makes cage exploration less efficient and thus slows down cooperative relaxation with respect to a passive glass. We finally weight this model agaist recent simulation results.

The Kuramoto model with higher-order interactions: secondary instabilities and collective chaos

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I. León and D. Pazó

In 1975, Kuramoto discovered a simple, analytically tractable model describing the transition from incoherence to collective synchronization. The Kuramoto model is the result of applying phase reduction to an ensemble of heterogeneous, globally coupled Stuart-Landau oscillators, and it is valid up to linear order in the coupling constant ϵ. Contrary to common wisdom, we show here that the next terms in the expansion, those of order ϵ^2, cannot be neglected. Complex collective states emerge from the combined effect of two different higher-order (i.e. nonpairwise) phase interactions present in the model. A truncation in a moment system allows us exploring the thermodynamic limit with Gaussian distributed natural frequencies.

Persistence of Heterodimensional Cycles

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A heterodimensional cycle is an invariant set of a dynamical system consisting of two hyperbolic periodic orbits with different dimensions of their unstable manifolds and a pair of orbits that connect them. For systems which are at least C^2, we show that bifurcations of a coindex-1 heterodimensional cycle within a generic 2-parameter family always create robust heterodimensional dynamics, i.e., chain-transitive sets which contain coexisting orbits with different numbers of positive Lyapunov exponents and persist for an open set of parameter values. In particular, we solve the so-called C^r-stabilization problem for the coindex-1 heterodimensional cycles in any regularity class $r = 2, \ldots, \infty, \omega$. The results are based on the observation that arithmetic properties of moduli of topological conjugacy of systems with heterodimensional cycles determine the emergence of Bonatti-Díaz blenders.

Generalized constitutive relation for nano-scale heat conduction

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The heat conduction processes at the nanmechanical scale often exhibit unusual behavior, including the size dependence of thermal conductivity, heat pulse propagation, fluctuations, and delay phenomena. We present a first-principle based approach that leads from a many-particle description to a nonlinear, stochastic constitutive relation for the modeling of transient heat conduction.

Utilizing transient dynamics: Controlling spiral wave chaos by small perturbations

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The dynamics during life threatening cardiac arrhythmias like ventricular fibrillation is governed by chaotic spiral/scroll wave dynamics. In ex-vivo experiments and numerical simulations, a phenomenon called self-termination can be observed frequently, where the chaotic dynamics terminates by itself without any interaction. We demonstrate what implications this observation has on the structure of the state space, and how this structure can be exploited for an efficient control of the dynamics via small but finite perturbations (localized in space and time). Furthermore, we discuss in general how an optimal configuration of perturbations can be achieved, in order to control the dynamics and terminate the chaotic spiral wave dynamics.

Numerical continuation of pattern forming fronts outside the homoclinic snaking region

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In this talk I will present numerical continuation results for pattern forming fronts in the planar Swift-Hohenberg equation outside of the homoclinic snaking region. The fronts can deposit stripes or cellular hexagons in their wake in the bistable region. I then use these results to provide a heuristic pattern selection criterion for pattern forming fully localised patches of hexagons.

Inferring excitatory and inhibitory connections in neuronal assemblies

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Alterations of neuronal networks' dynamics and information flow are implicated in several neurological disorders and brain pathologies, such as Alzheimer's disease, epilepsy, strokes, and tumors. In this context, reconstructing functional and effective connectivities in neuronal assemblies represents a useful approach to analyze information processing and, in some cases, to infer structural interactions among cells. Indeed, investigating how network connectivities change in pathological conditions is crucial in understanding the impact on network structure and emergent dynamics. With these premises, functional and effective connectivities represent a valuable biomarker of brain disorders. In this contribution, we discuss the use of a generalized transfer entropy measure to infer the effective connectivity in neuronal networks, including both excitatory and inhibitory connections. Specifically, we model biophysically realistic neuronal assemblies simulating both membrane voltage and calcium dynamics with different ground topologies. Further, we apply the transfer entropy on the simulated signals to reconstruct the corresponding effective networks, investigating networks' statistics in detail. We quantify dissimilarities between structural and effective networks, analyzing the power of this generalized transfer entropy to infer positive and negative connections. Finally, we discuss the application of the presented approach on experimental calcium imaging data.

Nonparametric learning of interaction kernels in mean-field equations of interacting particles

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F. Lu and Q. Lang

Systems of self-interacting particles/agents arise in multiple disciplines, such as particle systems in physics, flocking birds and swarming cells in biology, and opinion dynamics in social science. We consider the learning of the distance-based interaction kernel between the particles/agents from data consisting a trajectory of the population density. We present an efficient regression algorithm to estimate the interaction kernel, along with a systematic learning theory addressing identifiability and convergence of the estimators. We demonstrate our algorithm on three typical examples: the opinion dynamics with a piecewise linear kernel, the granular media model with a quadratic kernel, and the aggregation-diffusion with a repulsive-attractive kernel.

Stability and synchronization properties of delay coupled nano-lasers

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Coupled nanophotonic semiconductor lasers are a prototypical model for on-chip laser networks. Due to their small footprint and low power consumption they are promising light sources for a wide range of nanophotonic applications such as neuromorphic computing or secure optical communication. One crucial precondition for a successful photonic implementation is the knowledge about the synchronization stability. Although a lot is known about the dynamics of delay-coupled macroscopic lasers, the question about how the small size of nano-lasers and thus the small photon lifetime influences the stability under optical perturbations is still actively investigated [1], especially because the dynamic degree of freedom of the microscopic polarization and thus the full Maxwell Bloch equation system (class-C laser model), has to be considered.

We present an in-depth analysis of the dynamics for two non-identical class-C lasers with delayed coupling. Interestingly, an intermediate value of the polarization lifetime T_2 can be found where the relative stability is optimal despite the fact that, at high pump currents, a second laser threshold to chaotic emission exists. Thus, coupled nano-lasers are more stable than macroscopic lasers and can be tuned to show quite extensive locking ranges. The optimal T_2-value depends on the photon lifetime within the cavity. We can predict that nano-lasers show best synchronization properties for the case where the photon lifetime is equal to the polarization lifetime. For the case of strong optical coupling we find that a ratio of two-thirds between photon and polarization lifetime yields extensive parameter regions with stable and locked operation.

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Spectral analysis of topological finite rank systems

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In this talk we will present recent results about the characterisation of eigenvalues of one-dimensional subshifts of finite topological rank. This class of systems is the natural one when one wants to extend results coming from substitutions or linearly recurrent systems. This world consider the study of new types of aperiodic one-dimensional quasicrystals arising from uniformly bounded renormalisations.

The chaotic route to spiral wave control: an optogenetics approach.

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Fatal cardiac arrhythmias such as tachycardia and fibrillation are associated with the occurrence of spiral waves, the control of which is essential for the treatment of the disease. To date, the most effective means of controlling spiral waves in the heart have been high-voltage shock-based control methods. These rely on ensuring abrupt electrical synchronisation of the heart tissue. However, due to the many negative side effects associated with these methods, low energy techniques are in great demand. Low-energy techniques bring about termination of spiral waves by forcing them to drift towards non-excitable tissue boundaries with which they collide and extinguish their phase singularities. In particular, such drift can be induced by spatiotemporal modulation of domain excitability in optogenetically modified cardiac tissue. In this talk, I will demonstrate a low-energy optogenetics-based approach to suppress spiral waves by their controlled chaotisation and rapid drift.

Nonlocality induces chains of nested localized structures in lasers

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In a dissipative environment, the interplay between local nonlinearities and differential operators is sufficient to initiate self-organization and to generate an infinite variety of patterns. Among them, dissipative solitons (DSs) are of particular interest since they can be individually addressed by a local perturbation. These states are relevant for applications when implemented in optical resonators as light bits for information processing. DSs may form bound states, also called "molecules", via the overlap of their oscillating tails, which creates "covalent" bonds leading to stable equilibrium distances. In this contribution, we disclose a different kind of molecule composed by chains of nested DSs, which are globally bounded yet locally independent, like an ensemble of interlaced rings. We show that these molecules, which challenge the usual notion of local stability for DS compounds, can be obtained in the presence of a pointwise nonlocality coupling a field to a distant point in space. In order to observe such new bound states, we have studied their realization in an optical time-delayed system (TDS). A single-transverse mode vertical-cavity surface-emitting laser (VCSEL) is coupled to an external cavity that selects one of the linearly polarized states of the VCSEL (Y, say) and feeds it back twice, once with a time delay τ_f, and once with a delay τ_r after being rotated into the orthogonal direction (X). When τ_f is much larger than the laser time scales, this system may host vectorial DSs, which correspond to a full rotation of the polarization vector state on the Poincaré sphere, mainly along its equatorial plane. The nonlocal coupling is induced here by the additional delay τ_r, which leads to a nonlocality range d. We show that this optical TDS with nonlocal coupling can host molecules of covalent DS and also chains of nested DS.

Understanding the dynamics of biological and neural oscillator networks through exact mean-field reductions

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network cores including the visual and default mode networks. These findings are robust across human subjects (N=100) and are a fundamental network property within the wave picture. The renormalized connectome comprises the particle view in the limit of infinite transmission speeds and opens the applicability of graph theory to a wide range of novel network phenomena, including physiological and pathological brain rhythms. These two perspectives are orthogonal, but not incommensurable, when understood within the novel here proposed generalized framework of structural connectivity.

Network reconstruction and prediction of the transition to synchrony of coupled oscillators directly from data

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I. Leyva and C. Masoller

In this presentation I will discuss a data-driven approach for inferring the connectivity of an ensemble of coupled oscillators, and for identifying an early warning indicator of the synchronization transition. I will analyze synthetic data generated by simulating networks of Kuramoto phase oscillators, and empirical data recorded from Rossler-like chaotic electronic circuits. In both cases the oscillators are coupled in a sparse network that is unweighted, undirected, and has a random structure. I will show that the lag times between pairs of oscillators are informative for reconstructing the network (i.e., for classifying the links as existent or nonexistent). I will also show that the shift of the distribution of lag times towards zero lag values as the coupling strength increases is an early indicator of the transition to synchrony, even when this transition is explosive.

I. Leyva and C. Masoller, "Inferring the connectivity of coupled oscillators and anticipating their transition to synchrony through lag-time analysis", Chaos, Solitons and Fractals **133**: 109604 (2020).

Diffusive and curvature effects on symmetric instability in stratified vortices

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M. Mathur and S. Singh

We present a local stability analysis of an idealized model of stratified vortices that appear in geophysical settings. The base flow comprises an axisymmetric vortex with background rotation and an out-of-plane stable stratification, and a radial stratification in thermal wind balance with the out-of-plane momentum gradient. Solving the local stability equations along fluid particle trajectories in the base flow, the dependence of short-wavelength instabilities on Schmidt number Sc is studied, in the presence of curvature effects. In the diffusion-free limit, the well-known symmetric instability is recovered. In the viscous, double-diffusive regime, instability characteristics are shown to depend on three non-dimensional parameters (including Sc), and two different instabilities are identified: 1. a monotonic instability (same as symmetric instability at Sc = 1), and 2. an oscillatory instability (absent at Sc = 1). Separating the base flow and perturbation characteristics, two each of base flow and perturbation parameters (apart from Sc) are identified, and the entire parameter space is explored for the aforementioned instabilities. In comparison to Sc = 1, monotonic and oscillatory instabilities are shown to significantly expand the instability region in the space of base flow parameters as Sc moves away from unity. Neutral stability boundaries on the plane of Sc and a modified gradient Richardson number are then identified for both these instabilities. We conclude with a discussion of curvature effects, and the likelihood of monotonic and oscillatory instabilities in typical oceanic settings.

Optimizing charge-balanced pulse stimulation for desynchronization

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Deep brain stimulation (DBS) is a medical technique to modify pathological rhythms observed in Parkinson's disease and other pathologies. On a modeling level, the goal of the stimulation is often considered as desynchronization of a neuronal population. The current theoretical research aims at developing minimally invasive and energy-saving protocols by stimulating only at vulnerable phases. In this work, we take a step towards identifying the optimal timing and shape of stimulation to push a partially synchronized population of neurons towards incoherence.
To imitate neuronal synchrony, we exploit the Kuramoto-like model with noisy phase oscillators. The latter are characterized by their natural frequency and phase response curve (PRC). Within this framework, we model the pathological rhythm by a partially synchronous state that is the equilibrium solution of the system. To meet clinical prerequisites for DBS protocols, we model the stimulation by biphasic charge-balanced pulses. The mean-field phase determines the timing of a pulse unambiguously. The change in entropy and mean-field amplitude is then measured depending on the timing and shape of the stimulation.
As a result, we derive an effective PRC for the population that accounts for the weighting of the single oscillators' PRCs and the system's current state. The change in entropy in response to a short first kick of the stimulus turns out to be proportional to the first derivative of the effective PRC. Since this response is almost entirely annihilated by the stimulus' charge-balancing second kick, the total effect of a biphasic pulse is determined by the second derivative of the PRC. The theoretical findings are illustrated numerically in a model with two distinct asymmetrically weighted populations of oscillators, each population having one characteristic natural frequency and PRC.

Can we evaluate the fairness of a decision-making algorithm based on its internal dynamics?

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AI systems are used in decision-making processes in all aspects of human life, from predicting child mistreatment to granting a loan. Many of these algorithms are machine learning models trained on datasets containing features from individuals. They learn a representation of reality that will never be 100% accurate. Even a 'good representation' of the current reality can propagate historical discrimination based on legally protected features. These biases can be due to several factors, including human biases and data collection methods. To prevent biased algorithms, we need to understand where the bias originates and what it means for an algorithm to take 'fair decisions'. Although all elements of the development pipeline contribute to the fairness of a decision, usually only the training data and the output of a model are considered. However, another essential element of a model is how it takes its decisions. A model can have transparent training data and output but still be a black box when its reasoning is opaque. In this work, we present a novel technique to interrogate decision-making algorithms on how they make decisions. Through inverse design and by exploiting the mathematical structure of a neural network, we examine the canonical input a model expects to make a binary decision and what that tells us about the fairness of the model.

Gibbs posterior convergence and the thermodynamic formalism

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In this paper we consider the posterior consistency of Bayesian inference procedures when the family of models consists of appropriate stochastic processes. Specifically, we suppose that one observes an unknown ergodic process and one has access to a family of models consisting of dependent processes arising from dynamical systems. In this context, we consider Gibbs posterior inference, which is a loss-based generalization of standard Bayesian inference. Our main results characterize the asymptotic behavior of the Gibbs posterior distributions on the space of models. Furthermore, we show that in the case of properly specified models our convergence results may be used to establish posterior consistency. Our model processes are defined via the thermodynamic formalism for dynamical systems, and they allow for a large degree of dependence, including both Markov chains of unbounded orders and processes that are not Markov of any order. This work establishes close connections between Gibbs posterior inference and the thermodynamic formalism for dynamical systems, which we hope will lead to new questions and results in both non-parametric Bayesian analysis and the thermodynamic formalism.

Emerging criticality in heteroclinic dynamics

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Typical features of criticality are a proliferation of the dynamical repertoire, critical slowing down of the dynamics and a high sensitivity to perturbations in the vicinity of a critical parameter value. Such features support the storage, transformation and processing of information, in particular in applications to brain dynamics. A suitable framework to describe the transient dynamics in the brain is heteroclinic dynamics, in particular it may be applied to cognitive processes of the neural system. We consider various heteroclinic networks and zoom into the dynamics that emerges right at some bifurcation points. The observed features of criticality at these points and in their immediate vicinity qualify them as candidates for working points in systems which store and transfer information. As a novel feature we observe the emergence of a heteroclinic cycle between three manifolds that are densely covered by periodic orbits. Which periodic orbits are selected sensitively depends on the initial conditions due to hidden conservation laws. From a more general perspective, our results add to the observation that emergent features may arise at borderlines. Here, the borderlines separate different dynamical regimes in heteroclinic dynamics.

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General Nonlinear Impurity in a Photonic Array: Green Function Approach

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Introduction A common method for dealing with impurity problems is to make an educated guess about the impurity profile. This procedure usually works fine with linear impurities, but when nonlinearities enter the picture, it is no longer certain that this method will work in all cases. One elegant method for dealing with impurity problems is the technique of lattice Green functions. Even though this formalism was originally derived for linear problems, we show that it can also be extended to simple nonlinear problems. In this work, we consider a single general nonlinear optical impurity waveguide inside the bulk and at the surface of a one-dimensional linear waveguide array. By using an extension of the usual formalism of lattice Green functions, we compute in closed form the energy of the localized mode and its spatial optical power profile. We further specialize to the case of a saturable impurity and compute the transmission coefficient of plane waves across the saturable impurity guide. Results When the impurity guide is placed at the array bulk there is a bound state for any nonlinearity strength while for the surface case there is a minimum strength required. The transmission across the bulk impurity shows no resonances and it resembles a linear transmission. The self-trapping at the initial site shows no transition for the bulk case, but there is minimum nonlinearity strength to effect self-trapping for the surface impurity. Finally, the long-time propagation of optical power shows a ballistic behavior, with a speed that decreases with an increase in nonlinearity. All in all, the behavior of this saturable impurity is reminiscent of the case of a linear impurity, due to the fact that its effective nonlinearity is always smaller than the corresponding linear counterpart.

Glassy phase in dynamically balanced networks

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We study the dynamics of inhibitory balanced networks at varying (i) the level of symmetry in the synaptic connectivity; and (ii) the variance of the synaptic efficacies (synaptic gain). We find three regimes of activity. For suitably low synaptic gain, regardless of the level of symmetry, there exists a unique stable fixed point. Using a cavity-like approach, we develop a quantitative theory that describes the statistics of the activity in this unique fixed point, and the conditions for its stability. Increasing the synaptic gain, the unique fixed point destabilizes, and the network exhibits chaotic activity for zero or negative levels of symmetry (i.e., random or antisymmetric). Instead, for positive levels of symmetry, there is multi-stability among a large number of marginally stable fixed points. In this regime, ergodicity is broken and the network exhibits non-exponential relaxational dynamics. We discuss the potential relevance of such a "glassy" phase to explain some features of cortical activity.

Effect of the free surface on the stability and energy harvesting efficiency of a tensioned membrane in a uniform current.

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Flexible structures have recently been considered as alternative ways to extract energy from ocean waves (Alam 2012, Desmars et al 2018) or tidal currents (Trasch et al 2018), with the objective to find devices with complementary working characteristics compared to non-flexible energy harvesters. We investigate the dynamics of a finite length tensioned membrane with a localized linear damper to mimic energy extraction, which is placed in a uniform current parallel to a free surface. Such configuration resembles the so called Nemtsov's membrane (Nemtsov 1985), recently studied in details and generalized to finite depth cases by Labarbe & Kirillov (2020, 2021), or to the infinite flag configuration close to a free surface studied recently by Mougel & Michelin (2020). The above studies reveal the importance of the free surface on the stability of the system, due to interactions between surface waves and structural waves when a current is present. In the present study, focus is placed on both forcing by incident waves (as already reported by Achour et al 2020 for weak currents) and stability analysis in order to investigate the role of the current on wave energy extraction by a flexible membrane, and shed additional light on the possible instability mechanism. In this objective, a linear potential flow model coupled to a tensioned beam is considered, and numerical results computed with the finite elements code FreeFEM++ (Hecht 2012) interfaced by StabFEM solver (Fabre et al 2019) are presented for a large range of physical parameters covering both subcritical and supercritical regimes.

Dissipation in the standard nontwist map: the route to chaos and the coexistence of attractors

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The standard nontwist map (SNM) is a two dimensional area-preserving map, where the twist condition is violated locally, and it is used to describe the dynamical behavior of nontwist systems in general. The SNM exhibits an invariant torus, known as the shearless curve, twin island chain scenario and separatrix reconnection in the phase space, particular features for non-monotonic systems. The inclusion of dissipation in the nontwist map turns the shearless curve into an attractor, a robust shearless attractor that can survive under generic perturbations and different intensities of dissipation. In our survey, we study the Dissipative Standard Nontwist Map (DSNM), a dissipative version of the SNM, formed by the inclusion of a dissipation in the conservative map. By numerical simulations, we observe the transition to chaos on the shearless attractor by the Curry-Yorke route, a well established route for twist systems, where the quasi-regular attractor on the torus passes through a banded chaotic attractor and then become chaotic on the torus, as a control parameter of the system varies. We also observe the coexistence of different attractors in the phase space, implying multistability on the system. We analyze the different coexistence scenarios by the basin entropy portrait, where the basin entropy and the boundary basin entropy inform us about the interactions of basins of attraction from different attractors in the phase space.

Active turbulence, a Lévy walk away from inertial

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Dense active suspensions, like bacterial swarms, display states of complex self-organization like active turbulence – flows that are vortical, chaotic and multi-scale, hence reminiscent of inertial turbulence. However, some experiments suggest that microorganisms in active suspensions can manifest specialized movement patterns like Lévy walks leading to anomalous diffusion, which facilitates efficient foraging and survival. Detecting this essential biological behaviour has so far remained theoretically elusive. Using a generalized hydrodynamic model of "active fluids", we show how anomalous super-diffusive and associated Lévy walks masquerade as a crossover from ballistic to diffusive scaling in measurements of mean-squared-displacements. We trace the origins of this anomalous behaviour novel oscillatory "streaks" in the bacterial flow, which has no analogue in high Reynolds number turbulence. Thus, while laying the theoretical framework for how activity drives living systems to defy bounds on inanimate matter, our work allows us to underline the essential differences between active and inertial turbulence.

Semiclassical calculation of spectral correlation functions for chaotic systems

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We present a semiclassical approach to n-point spectral correlation functions of quantum systems whose classical dynamics is chaotic, for arbitrary n. The basic ingredients are sets of periodic orbits that have nearly the same action and therefore provide constructive interference. We calculate explicitly the first correlation functions, to leading orders in their energy arguments, for both systems with and without time reversal invariance. The results agree with corresponding predictions from random matrix theory, thereby giving solid support to the conjecture of universality. For systems without time-reversal invariance we then extend this result to all orders in perturbation theory for the non-oscillatory parts of all correlation functions, showing that the off-diagonal contributions to these correlation functions cancel and the conjectured universality holds. The innovation that allows the latter calculation to be performed is the introduction of an auxiliary matrix model which is governed by the same diagrammatic rules as the semiclassical approach and which can be solved exactly.

Laminar Chaos in Experiments: Nonlinear Systems with Time-Varying Delays and Noise

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Due to environmental fluctuations that influence delay generating processes such as transport processes, delays in nature are typically not constant, rather time-varying. In [1] it is demonstrated that there are two types of periodically time-varying delays. Systems with a so-called conservative delay exhibit qualitatively the same dynamics as systems with constant delay. In contrast, the dynamics of systems with dissipative delay differs from constant delay dynamics, which leads, for instance, to a different scaling behavior in the Lyapunov spectrum.

As a consequence of this dichotomy, a new type of chaos called Laminar Chaos was discovered in systems with dissipative time-varying delay [2]. It is characterized by nearly constant laminar phases with periodic duration, where the intensity of the laminar phases varies chaotically from phase to phase. In contrast to the typically high-dimensional Turbulent Chaos, which is observed in systems with conservative (including constant) delay, Laminar Chaos is low-dimensional.

In this talk and in our recent publications [3,4], we demonstrate experimentally and theoretically that Laminar Chaos is a robust phenomenon, which survives noise that is inherent to every experiment. Therefore, we provide the first experimental observation of Laminar Chaos by studying an optoelectronic feedback loop with time-varying delay. We elaborate the robust features of Laminar Chaos and provide a time-series analysis toolbox for their detection. The toolbox is benchmarked by experimental data and by time-series of a nonlinear delayed Langevin equation with time-varying delay.

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Globally Resonant Homoclinic Tangencies

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The attractors of a dynamical system govern its typical long time behavior. The presence of many attractors is an exotic phenomenon and occurs in diverse applications. Periodic orbit is one such example of an attractor. Since 1970 researchers have shown that there exists a sequence of single-round periodic solutions near the homoclinic tangency, but generically all of them are unstable. In this talk, I will discuss about a special homoclinic tangency known as "globally resonant homoclinic tangencies" that allows us to have infinitely many stable single-round periodic solutions. It is found that the phenomenon of infinite coexistence of stable single-round periodic solutions is codimension-three in the orientation-reversing case while it is codimension-four in the orientation-preserving case. I will then illustrate this phenomenon by giving a minimal example.

Matter-wave turbulence in a quantum gas

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The recent production of homogeneous Bose gases [1] has opened exciting possibilities to study far-from-equilibrium many-body dynamics in clean uniform quantum fluids. In this talk, I will present our study of the emergence of a turbulent cascade in a homogeneous Bose fluid forced out of equilibrium on a large scale using a spatially-uniform force [2]. In contrast to classical fluids where the dissipation scale is set by the viscosity of the fluid, the turbulent cascade of our quantum gas ends when the particles kinetic energy exceeds the laser-trap depth. This simple mechanism allows us to effectively tune the dissipation scale where particles (and energy) are lost. Using this new knob, we directly measure turbulent fluxes and observe in real time the propagation of the cascade front in momentum space [3]. Once the cascade front has reached the dissipation scale, a scale-invariant steady state is established over the entire inertial range.

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Fast linear response algorithm for differentiating stationary measures of chaos

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We devise a new algorithm, called the fast linear response algorithm, for accurately differentiating SRB measures with respect to some parameters of the dynamical system, where SRB measures are fractal limiting stationary measures of chaotic systems.

The core of our algorithm is the first numerical treatment of the unstable divergence, a central object in the linear response theory for fractal attractors. We derive the first computable expansion formula of the unstable divergence, where all terms are functions rather than distributions. Then we give a 'fast' characterization of the expansion by renormalized second-order tangent equations, whose second derivative is taken in a modified shadowing direction, computed by the non-intrusive shadowing algorithm.

The new characterization makes the algorithm efficient and robust: its main cost is solving u, the unstable dimension, many first-order and second-order tangent equations, and it does not compute oblique projections. Moreover, the algorithm works for chaos on Riemannian manifolds with any u; its convergence to the true derivative is proved for uniform hyperbolic systems. The algorithm is illustrated on an example which is difficult for previous methods. The procedure list is easy to understand and implement.

Single-cell modeling of Caenorhabditis elegans neurons: from sensory to motor neurons

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TBA

Synchronization of low Reynolds number plane Couette turbulence

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We demonstrate that a separation of the velocity field in large and small scales according to a streamwise Fourier decomposition identifies subspaces with stable Lyapunov exponents and allows the dynamics to exhibit properties of an inertial manifold, such as the synchronization of the small scales in simulations sharing the same large scales or equivalently the decay of all small scale flow states to the state uniquely determined from the large scale flow. This behaviour occurs for deviations with streamwise wavelength smaller than 130 wall units, which was shown in earlier studies to correspond to the streamwise spectral peak of the cross-flow velocity components of the top Lyapunov vector of the turbulent flow.

R-tipping and saddle-node bifurcation for quadratic nonautonomous ODEs

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An in-depth analysis of nonautonomous bifurcations of saddle-node type for scalar differential equations $x' = -x^2 + q(t)\,x + p(t)$, where $q\colon \mathbb{R} \to \mathbb{R}$ and $p\colon \mathbb{R} \to \mathbb{R}$ are bounded and uniformly continuous, is fundamental to explain the absence or occurrence of rate-induced tipping for the differential equation $y' = (y - (2/\pi)\arctan(ct))^2 + p(t)$ as the rate c varies on $[0, \infty)$. A classical attractor-repeller pair, whose existence for $c = 0$ is assumed, may persist for any $c > 0$, or disappear for a certain critical rate $c = c_0$, giving rise to rate-induced tipping. A suitable example demonstrates that this tipping phenomenon may be reversible.

Rate-Induced Tipping of the Compost Bomb: Sizzling Summers, Metastable Zombie Fires and Heteroclinic Canards

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Once ignited, peatland fires may smolder for months spewing out smoke, toxic fumes, and carbon dioxide. This phenomenon occurs across a diversity of regions such as Indonesia, Canada, Australia, and Siberia. With fire frequency expected to increase under climate change, the carbon released would be significant for the global climate–carbon cycle. Heat produced by microbial respiration is thought to be a key contributor, and this is the basis of the 'Compost-Bomb' instability, a theorized runaway heating of peat soils when atmospheric temperature rises faster than some critical rate, first proposed in [Luke & Cox, European Journal of Soil Science (2011), 62.1] and analysed in [Wieczorek et al, Proceedings of the Royal Society A (2011), 467.2129].

Here, the original soil carbon-temperature model of Luke & Cox is augmented with a non-monotonic microbial respiration function, for a more realistic process representation. This gives rise to a meta-stable state, reproducing the results of [Khvorostyanov et al, Tellus (2008), 60B] where a complex PDE model is used. Two non-autonomous climate forcings are examined: (i) a rise in mean air temperature over decades (ii) a short-lived extreme weather event, with the rate-induced compost bomb observed in each. Using techniques of compactification, singular perturbation and rate-induced tipping, we reduce the compost-bomb problem to one of heteroclinic orbits, uncovering the tipping mechanism for each climate change scenario.

Local bifurcation structure of a bouncing ball system with a piecewise polynomial function for table displacement

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The system in which a small rigid ball is bouncing repeatedly on a heavy flat table vibrating vertically, so-called the bouncing ball system, has been widely studied. Under the assumption that the table is vibrating with a piecewise polynomial function of time, the bifurcation diagram changes qualitatively depending on the order of the polynomial function. We elucidate the mechanism of the difference in the bifurcation diagrams by focusing on the two-period solution. In addition, we derive the approximate curve of the branch close to the period-doubling bifurcation point in the case of the piecewise cubic function of time for the table vibration. We also performed numerical calculation, and we demonstrate that the approximations well reproduce the numerical results.

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Patient-specific network connectivity combined with a next generation neural mass model to test clinical hypothesis of seizure propagation

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Dynamics underlying epileptic seizures span multiple scales in space and time, therefore, understanding seizure mechanisms requires identifying the relations between seizure components within and across these scales, together with the analysis of their dynamical repertoire. In this view, mathematical models have been developed, ranging from single neuron to neural population. In this study we consider a neural mass model able to exactly reproduce the dynamics of heterogeneous spiking neural networks. We combine the mathematical modelling with structural information from non-invasive brain imaging, thus building large-scale brain network models to explore emergent dynamics and test clinical hypothesis. We provide a comprehensive study on the effect of external drives on neuronal networks exhibiting multistability, in order to investigate the role played by the neuroanatomical connectivity matrices in shaping the emergent dynamics. In particular we systematically investigate the conditions under which the network displays a transition from a low activity regime to a high activity state, which we identify with a seizure-like event. This approach allows us to study the biophysical parameters and variables leading to multiple recruitment events at the network level. We further exploit topological network measures in order to explain the differences and the analogies among the subjects and their brain regions, in showing recruitment events at different parameter values. We demonstrate, along the example of diffusion-weighted magnetic resonance imaging connectomes of 20 healthy subjects and 15 epileptic patients, that individual variations in structural connectivity, when linked with mathematical dynamic models, have the capacity to explain changes in spatiotemporal organization of brain dynamics, as observed in network-based brain disorders.

Moving bumps in theta neuron networks

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We consider large networks of theta neurons on a ring, synaptically coupled with an asymmetric kernel. Such networks support stable "bumps" of activity, moving with a constant speed if the coupling kernel is asymmetric. We investigate the effects of the kernel asymmetry on the existence, stability and speed of these moving bumps using continuum equations formally describing infinite networks. Depending on the level of heterogeneity within the network we find complex sequences of bifurcations as the amount of asymmetry is varied, in strong contrast to the behaviour of a classical neural field model.

Minimum time control and bifurcations around nilpotent equilibrium

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When one is interested in the singularities of minimum time control affine problems, necessary conditions for optimality boils down to the study of an Hamiltonian system with singularities. After regularisation, generic systems can be interpreted as a dynamical system with parameter admitting a bifurcation around a nilpotent equilibrium. We study this phenomena and conclude towards the regularity of optimal solutions.

Spike propagation in a nanolaser-based optoelectronic neuron

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With the recent growth of Artificial Intelligence and Neural Networks systems, alternatives to the CMOS architecture are in development to run these algorithms efficiently in terms of speed, size and power consumption. In this study, a neuromorphic, optoelectronic device consisting of a resonant tunneling diode (RTD) and a nanolaser diode (LD) is demonstrated as an excitable pulse generator. The response pulse is characterized

in terms of its width, amplitude, response delay, distortion and jitter times. Finally, two RTD-LD units are integrated via a photodetector and their feasibility to produce and propagate optical pulses is studied.

Multiobjective optimization of metabolic control systems

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Progress in genetic engineering now allows the construction of molecular circuits inside living cells. In this talk I will present our recent work on the optimisation of molecular circuits designed for production of chemicals in the food, pharma and energy sectors. We employ Pareto optimality to quantify the design tradeoffs between costs and benefits of production, as well as the system sensitivity to perturbations relevant in applications. Starting from two-timescale nonlinear dynamical model, we solve cost-benefit optimisation problems for a range of systems built in the wetlab so far. The results reveal relations between parameter fine-tuning and the resulting close-loop performance, thus providing guidelines for the design of such systems in practice.

In silico–in vitro approach to study and control cardiac arrhythmias

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Sudden cardiac death as a result of cardiac arrhythmias is the leading cause of death in the industrialized countries. Although cardiac arrhythmias has been studied well over a century, their underlying mechanisms remain largely unknown. One of the main problems is that cardiac arrhythmias occur at the level of the whole organ only, while in most of the cases only single cell experiments can be performed. Due to these limitations alternative approaches, such as multiscale biophysical modelling of the heart, are currently of great interest. Such methodology is extremely valuable if it combined with experimental and clinical methodology. In my talk I will present results of research which combine usage of modelling and modern experimental techniques. In particular, I will report on studies in which properties of cardiac tissue were manipulated using optogenetics and show how this technology can be used to study basic properties of cardiac propagation and to control cardiac arrhythmias using Attract-Anchor-Drag method [1]. I will also report on new data driven methods to identify sources of cardiac arrhythmias from clinical mapping data using a novel methodology of DG-mapping developed in our group [2].

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

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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.

Chaotic transients and dynamical response of coupled oscillators

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We will present examples of transient chimera states in networks of coupled oscillators and demonstrate their susceptibility against small but finite local perturbations at the boundary between coherent and incoherent dynamics [1]. Furthermore, we will discuss aspects of information processing using driven dynamical networks.

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Dynamics of the processing of orientation precision in the primary visual cortex

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The primary visual cortex (V1) processes complex mixtures of orientations to build neural representations of our visual environment. It remains unclear how V1 adapts to the highly volatile distributions of orientations found in natural images. We used naturalistic stimuli and measured the response of V1 neurons to orientation distributions of varying bandwidth. Although broad distributions decreased single neuron tuning, a neurally plausible decoder could robustly retrieve the orientations of stimuli from the population activity at all bandwidths. This decoder demonstrates that V1 population co-encodes orientation and its precision, which enhances population decoding performances. This internal representation is mediated by temporally distinct neural dynamics and supports a precision-weighted description of neuronal message passing in the visual cortex.

Evolution of Scroll Ring in Myocardial Wall

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Scroll waves are implicated in the most dangerous cardiac arrhythmia known as ventricular fibrillation, the main cause of sudden cardiac death. Scroll waves are organized around phase singularity lines, filaments. The filaments are local breaks of the excitation fronts. The fronts are thin compared to ventricular wall and can be viewed as a 2D surface. Consequently, local breaks of the front can be viewed as holes in this surface, which give rise to filaments with close loop topology (rings). One of the key parameters controlling filament dynamics is filament tension which can be positive or negative depending on tissue excitability. In excitable media with spatially uniform parameters, the positive tension makes rings collapse, healing the front breaks, and terminating the scroll wave activity. It would be reasonable to assume in the normal heart the tension should be positive, which would make the scroll wave formation more difficult and thus protect the heart from arrhythmias. However, the heart wall has a significant inherent non-uniformity, which could affect the filament dynamics and the course of arrhythmia. Such non-uniformity is so-called twisted anisotropy, resulting from large differences in fiber orientation across the thickness of the myocardial wall. Mathematically it can be described by spatial gradients of the diffusivity tensor in the reaction-diffusion equations governing propagation of the action potential in the heart. Here we explore computationally and analytically the dynamics of ring-shaped filaments in the presence of twisted anisotropy. We demonstrate that the gradients of diffusion tensor components cause major deformation of the ring and change its dynamics. In case of positive tension, we demonstrate the for a broad range of initial conditions the filament does not collapse but forms quasi-stable intramural L-shaped filaments. The results are discussed in the context of filament dynamics in transillumination tissue experiments.

Spatio-temporal structure of the connectome organizes the large scale brain activity

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Networks in neuroscience determine how brain function unfolds. Perturbations of the network lead to psychiatric disorders and brain disease. Brain networks are characterized by their connectomes, which comprise the totality of all connections, and are commonly described by graph theory. This approach is deeply rooted in a particle view of information processing, based on the quantification of informational bits such as firing rates.

Oscillations and brain rhythms demand, however, a wave perspective of information processing based on synchronization. We extend traditional graph theory to a dual particle-wave-perspective, integrate time delays due to finite transmission speeds and derive a renormalization of the connectome. When applied to the data base of the Human Connectome project, we explain the emergence of frequency-specific

Condensation of classical optical waves in multimode fibers: Theory and experimental observation

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The wave turbulence theory predicts that a classical system of random waves exhibits a process of condensation, which originates in the singularity of the Rayleigh-Jeans equilibrium distribution. We report the experimental observation of the transition to condensation of light waves propagating in a multimode fiber, i.e., in a conservative Hamiltonian system without thermal heat bath [1]. The chemical potential reaches the lowest energy level at the transition to condensation, which leads to the macroscopic population of the fundamental mode of the optical fiber. The thermodynamic properties of the classical condensation process are discussed. On the basis of the wave turbulence theory, we have derived a kinetic equation describing the nonequilibrium evolution of the system and that accounts for the presence of the structural disorder inherent to the propagation of light in multimode fibers [2,3]. The theory reveals that the disorder significantly accelerates the process of thermalization, which explains the fast process of condensation observed in the experiments [1].

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Low-dimensional firing rate dynamics for populations of renewal spiking neurons

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To describe the collective dynamics of large populations of neurons, one often resorts to traditional firing-rate, or neural-mass, models. These models are low dimensional and therefore analytically tractable. But they are also heuristic and cannot capture more complex dynamics of stochastic spiking neurons. Here, we will present a systematic reduction of the population activity of general renewal-type neurons that can account for neuronal refractoriness and spike synchronization dynamics. The derivation is based on an eigenmode expansion of the associated refractory density equation. Already a first-order approximation yields an accurate low-dimensional firing rate model that captures spike synchronization effects and fast transient dynamics at stimulus onset. The characteristic time scales of the system can be determined through a simple eigenvalue formula in terms of the interspike interval density or the survival function of the renewal process. The eigenvalue formula thus directly links microscopic neuronal properties to observed macroscopic behavior.

Self-Induced Synchronisation by large delay

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This work deals with periodic behavior of differential equations with time delay. Starting from a smooth vector field f in 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, which number increases as the delay becomes larger and larger. We give a formula for the frequencies of these periodic orbits, valid at first order in eta. Hence trajectories present a form of synchronization in clusters induced by the time delay, a phenomenon which is widely seen in opto-electronic networks.

Our approach uses in a large part classical nonlinear dynamical systems methods valid for ODEs. It is based on perturbation results for semi-flows on Banach spaces due to P. Bates, K. Lu and C. Zeng [2] and on a construction of an invariant, globally attracting manifold for the semi-fow of our equation (similar constructions have been done in the past in more general settings notably by Xu-Yan Chen, Jack K. Hale, and Bin Tan). Our result somehow completes already known results on reappearance of periodic orbits in time-delay equations due to S. Yanchuk and P. Perlikowski [1], and on multistable states in phase reduction models [3].

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Collective dynamics of coupled oscillators

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In the last years the evolution of coupled nonlinear oscillators has attracted an increasing interest for the several freaky regimes that may emerge even when the single units are simple phase oscillators. I will pay a special attention to collective properties, where, by "collective" I mean the spontaneous emergence of macroscopic features, such as the synchronization testified by a nonzero Kuramoto order parameter and accompanied by a nontrivial dynamics. The role of heterogeneity, coupling function, amplitude fluctuations, competition between excitation and inhibition, and coupling sparseness will be reviewed illustrating the various regimes that have been so far identified.

Competition drivers in confined cellular aggregates: Does dead matter matter?

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Competition of different species or cell types for limited space is relevant in a variety of biological processes such as biofilm development, tissue morphogenesis and tumor growth. Defining a fitness for each cell type that predicts the outcome of non-adversarial competition is non-trivial, as it depends on how processes such as growth, proliferation and the degradation of cellular matter are regulated in confinement in order to achieve the dynamic steady state known as homeostasis. Here, we show that passive by-products of the processes maintaining homeostasis can significantly alter fitness. Even for purely pressure-regulated growth, this enables cell types with lower homeostatic pressure to outcompete those with higher homeostatic pressure. We develop a theoretical framework that explains this effect and test it in an agent-based computational model that includes finite-time mechanical persistence of dead cells and thereby decouples the density of growing cells from the homeostatic pressure. Our results suggest that self-organization of cellular aggregates into active and passive matter can be decisive for competition outcomes and that optimizing the proportion of growing (active) cells can be as important to survival as mechanical bulk properties.

A biased survey on deterministic nonautonomous bifurcations

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We survey the developing bifurcation theory for deterministic nonautonomous dynamical systems over the last 20 years. This includes various approaches ranging from spectral theory (Lyapunov vs. Sacker-Sell) to the notion of a bifurcation (topological vs. analytical) itself. Moreover, we remark on the numerical analysis required in order to verify corresponding assumptions.

Diffusion and dispersion in anisotropic magnetohydrodynamic turbulence

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Magnetohydrodynamic (MHD) turbulence structured by a large-scale magnetic field is an essential aspect of interstellar or interplanetary plasmas. Here we investigate diffusion and dispersion in anisotropic MHD turbulence. We adopt the Lagrangian viewpoint, the natural point of view to study diffusion, and construct statistics based on the trajectories of Lagrangian tracer particles.

From the motions of these tracer particles, we produce Lagrangian statistics such as single-particle diffusion, two-particle dispersion, and velocity autocorrelations. We also demonstrate new Lagrangian statistics developed to understand anisotropic turbulent dispersion. Simulation results will be presented that are performed using grid sizes up to 2048^3. Diffusion and transport processes in turbulent plasmas constitute fundamental astrophysical problems; a clear understanding of these processes is needed in order to produce improved theoretical models for the diffusion and transport of energetic particles, including cosmic rays.

Experimental observation of violent relaxation in a nonlinear optical system

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Gravity is the most important interaction at cosmological scales; its long range nature leads to collective effects which lead to the formation of out-of-equilibrium quasi stationary states of aggregation, such as galaxies or galactic halos. This process, called violent relaxation or collision-less relaxation [1], takes place without any increase of entropy, differently from the well-known relaxation towards thermodynamic equilibrium. It is characterized by two phenomena: mixing [2], caused by the motion of particles in a non-harmonic potential created self-consistently by the mass distribution, mixing the phase space; and Landau damping, that is the mixing of the energy of the particles due to the potential created by the mass distribution not being stationary in time. The process of self-gravitating collapse and formation of galaxies and globular clusters, via this violent relaxation mechanism, is still not well understood. Moreover, astrophysical time scales are so large that direct observations are impossible; it is then useful to perform experiments in analogue systems. In this work we present the results of an experiment in a nonlinear optical medium with thermal nonlocal nonlinearity, analogue to a self-gravitating system described by the Newton-Schrödinger Equation (NSE) where quantum effects arise to macroscopic galactic scales. In this experiment we collect information on the evolution of the intensity and phase profiles of a laser beam undergoing a nonlinear, nonlocal propagation, by means of a technique called Off-Axis Digital Holography. For the first time to our knowledge, we experimentally observe the characteristic features of violent relaxation, such as filamentation of phase space and Landau damping. By exploiting the analogy between the Nonlinear Schrodinger Equation (which characterises the evolution of the beam in the nonlinear medium) and the NSE we can show Landau damping and the process of violent relaxation for the optical wavefunction.

The role of fractal and reflecting connectivities in networks of FitzHugh-Nagumo oscillators

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Motivated by MRI and fMRI studies addressing the connectivity between neurons in the human brain, we use coupled FitzHugh-Nagumo (FHN) oscillators to investigate synchronization patterns and the propagation of electrical activity in the brain. First, we apply hierarchical connectivity as reported in Ref. [1]. Namely, in a 1D ring geometry, each FHN oscillator is connected to all oscillators belonging to a given Cantor set. Our results indicate that chimera states are formed on the ring, and for appropriate adjustment of the coupling strength, the incoherent parts of the chimera states split in secondary formations mirroring the fractal geometry of the connectivity [2]. Different MRI studies addressing common connectivity patterns in the brain of many individuals have revealed that the neuron axons connecting corresponding regions in the left and right hemispheres are common to all healthy individuals [3]. This type of connectivity is called ”reflecting”. Using the FHN model in a ring network with reflecting connectivity, our numerical results indicate that for excitatory (inhibitory) coupling strength coherent (incoherent) oscillatory regions develop and reside in the junctions between the two semirings [4]. These conclusions support the idea that the connectivity between brain neurons determines local synchronization patterns in the brain.

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Pacemaker effects in Brain Dynamics

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We study the dynamics of neuron networks in healthy brains and brains affected by tumor. The brain connectivity in each case is recorded by MRI imaging. Using this data, we perform numerical simulations where the FitzHugh-Nagumo and the Leaky Integrate-and-Fire models are employed to represent the local neural dynamics. The numerical simulations indicate that in the healthy brain chimera-like states develop, where regions with high white matter concentrations in the direction connecting the two hemispheres act as the coherent domain, while the rest of the brain presents incoherent oscillations. To the contrary, in brains with destructed structures, traveling waves are produced initiated at the region where the tumor is located. These areas act as the pacemaker of the waves sweeping across the brain [1]. Artificial networks in 2D are also employed to elucidate the mechanisms which produce the pacemaker effect.

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Overload dynamics of a magnetic gear with two cogging-free operation modes

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The coupling of two rotating spherical magnets is investigated experimentally. For two specific angles between the input and output rotation axes, a cogging-free coupling is observed, where the driven magnet is phase-locked to the driving one. The striking difference between these two modes of operation is the reversed sense of rotation of the driven magnet. For other angles, the experiments reveal a more complex dynamical behaviour. The experimental results can be understood by a mathematical model based on pure dipole-dipole interaction, with the addition of adequate friction terms [1]. Like all magnetic couplings, the setup contains intrinsic overload protection, where the dynamic answer of the couplings with cogging to an overload seems particularly rich.

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Nonlinear Optical Applications of Liquid Crystal Light Valves

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Liquid crystals offer a unique versatile platform for optical applications and light manipulation thanks to their transparency in a wide range of the electromagnetic spectrum, optical selectivity and high birefringence. Liquid crystal light-valves (LCLV) associate liquid crystal with a photosensitive material, allowing the realization of optical addressable spatial light modulators. These electro-optical devices allow achieving efficient control of the phase and amplitude of optical beams at various wavelengths and optical powers. Moreover, LCLV provide a nonlinear optical effect equivalent to that of Kerr media, easily controllable via an external bias voltage, efficient over a large transverse size, with homogenous spatial response and good spatial resolution. Thanks to these properties, LCLV are ideal components for implementing nonlinear optical experiments, particularly, optical wave-mixing and beam coupling. I will show different examples of nonlinear optical applications of LCLV, as two-wave mixing, optical rogue waves and manipulation of vortex beams.

Lagrangian descriptors and regular motion

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Lagrangian descriptors introduced a decade ago have revealed as a powerful tool to unveil the intricacies of the phase space of dynamical systems in a very easy way [1]. They have been extensively used to study chaotic motion in a variety of different situations [2, 3], but much less attention has been paid to applications to the regular regions of phase space. In this communication, we show the potential of this recent mathematical tool, when suitably manipulated, to compute and fully characterize invariant tori of generic systems [4]. To illustrate the method, we present an application to the well known Hénon-Heiles Hamiltonian, a paradigmatic example in nonlinear science. In particular, we demonstrate that the Lagrangian descriptors associated with regular orbits oscillate around an assymptotic value when divided over the integration time, which enables the computation of the frequencies of invariant tori.

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Twist effects of quantum vortex defect

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Here we present new results on the physical effects of phase twist superposition on an isolated vortex defect governed by the Gross-Pitaevskii equation (GPE). From the modified Hamiltonian we derive a stability criterium and give rigorous proof that a superposed global phase twist determines the production of a secondary defect due to a Aharonov-Bohm topological instability. Alternatively, if the phase twist is localized the instability determines pure writhe deformation at the expense of twist. These results may have important implications in the study of condensates. This is joint work with Matteo Foresti (UniMiB).

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Local Lyapunov exponents of ENSO Events of Coastal Temperatures in the South-Eastern Pacific

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In this work we study from the point of view of the theory of non-linear dynamic systems the effect of El Niño on the coastal temperatures on the east coast of the South Pacific, characterized by the Humboldt Current System (HCS). Through a non-linear analysis of five long time series of atmospheric and oceanic temperatures distributed between 18 ° S and 45 ° S, covering the El Niño events of 1982/83 and 1997/98, we found that all the stations studied along the Along this transect show positive local Lyapunov exponents for temporary windows of months in the case of oceanic temperatures and an annual window for atmospheric temperatures. The study suggests that the South Pacific climate system is going through periods of stability and instability, the latter occurring during El Niño events.

Time delays in the cell: from biochemical mechanism to oscillations

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The cell is one of the most basic units of life, but is itself teeming with complexity. Cells act as little containers for chemical reactions involving genes, RNA and proteins. At the same time, they contain many spatial structures which additionally regulate those reactions. Mathematical modeling has played an important role in understanding how all these components work together and give rise to cellular functions. Models exist on a range of scales, from conceptual models consisting of a handful of ordinary differential equations, to spatial stochastic models involving numerous different genes and proteins. Often, the complexity of an extended reaction mechanism or spatial effect is summarized into a time delay, which is directly introduced in the equations. However, it is not always clear how to best do this, and what the effect of the time delay, and its specific form, is on the behavior of the system. A typical consequence of a time delay is oscillatory behavior, with examples from biology including the circadian clock or the cell division cycle. The way the time delay is modeled in these systems may have an important effect on the properties of the oscillation. Additionally, when such oscillatory systems are coupled in space through diffusion, spatial waves can form. Such waves play a role in the transmission of information inside the cell, and their properties may depend on the presence of a time delay.

In this talk, I will discuss time delays in cell biology and their effect on biochemical oscillations and waves. After an overview of delay-generating mechanisms in the cell and their mathematical modeling, I will discuss how such delays affect oscillations, with a focus on the oscillations seen in the cell division cycle.

How to make a flow oscillate in a simple reactive system

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When two miscible reactants A and B, initially separated in space, react upon diffusive mixing, the product C can generate convective flows by locally changing the surface tension of the solution or its density. We present a new mechanism through which self-sustained chemical oscillations and waves can be maintained in batch conditions with a simple A+B→C reaction, in the absence of any nonlinear chemical feedback or external trigger. By means of numerical simulations, we show that, if the surface tension increases sufficiently during the reaction, a transient Marangoni oscillatory flow can be observed. The antagonistic coupling with buoyancy-driven convection, arising from density changes during the chemical reaction, can enhance the oscillatory instability, leading to self-sustained oscillations. The dynamics is characterized in the relevant parametric space spanned by the thickness of the solution layer and the Marangoni and buoyancy numbers, quantifying the effect of each chemical species on the surface tension and solution density, respectively.

Modelling open systems with networks of nonautonomous phase oscillators

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Thermodynamic openness is a common occurrence in complex systems, particularly for those that are living. In the example of cells, without exchanges of matter and energy across their system boundaries, they would be unable to maintain necessary ion concentrations and expel waste products. This presents a challenge to traditional physical dynamics modelling techniques, which have often been developed with closed systems in mind.

Constructing models that represent system processes with phase oscillators can much more easily allow for an open system than differential equations of the processes' various mass exchanges. The openness of biological systems also generates time-dependent dynamics, as the frequent exchanges of matter and energy perturb the system to new states. These elements can be combined by networks of nonautonomous phase oscillators, each representing a system process. This will be presented in the context of the energy metabolism of a cell [1].

This system of driving and driven networks of nonautonomous oscillators builds on the definition of chronotaxic systems, which demonstrated that time-dependent driving induces greater system stability [2], and the discovery of intermittent synchronisation in a single driven nonautonomous network [3]. An analysis of the synchronisation dynamics of this new model in the context of these past findings will also be presented.

These dynamics can also be further analysed in altered parameter states, representing, for example, the relatively increased glycolysis of cancer and COVID-19, to learn more of the behaviour of these states at a cellular level [1, 4].

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Study and modeling of filtering of biological noise by gene regulatory networks in animal development

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The biological noise is known as the heterogeneity of gene expression in cells expressing a gene. This heterogeneity is due to the kinetics of the reactions that makes part of the gene expression system. On the other hand, in development, organisms grow with the same spatial and temporal patterns, with few variations among individuals. For this reason, it is expected that in the differentiation process and pattering formation the noise should be filtered. Here we evaluated and propose the gene expression network motifs as a mechanism of buffering biological noise in development. For this, we evaluated the noise filtering capacity of three network motifs involve in patterning formation in development. Each cell that expresses a determinate network motif was represented as a set of stochastic differential equations. These equations included the mechanism that produces noise in gene expression. The noise was measured with the Fano Factor. And it was estimated for each network motif in a range of kinetic parameters, in an unicellular system without diffusion and multicellular system with diffusion, and in a multicellular system with diffusion and a random number of neighbors by cell. The size of the system was also evaluated. For all network motifs, the noise is bigger for the lower values of kinetic parameters. Increasing the diffusion rate did not necessarily imply a decrease in noise. In fact, there are a variety of effects depending of the network motif and the set of kinetic parameters. The increase in the size of the multicellular system did not have an effect on the noise filtering for some motifs. The number of neighborhoods of the cell in the multicellular systems has a different effect on the noise filtering depending on the network motif, set of kinetic parameters, diffusion rates, and size of the system.

Waves and patterns in cell-free cytoplasmic extracts

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Upon fertilization, the early Xenopus leavis 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 (tens of microns). Such frog eggs can be deconstructed into their basic components, such as lipids, yolk, organelles, cytoplasm, etc. Using Xenopus cell-free cytoplasmic extracts, many cellular processes have been reconstituted and studied in vitro.

Biochemically, clock-like transitions between interphase (during which DNA is copied) and mitosis (during which the cell divides) can be recreated in cell-free extracts. The transition from interphase to mitosis has been shown to be controlled by biochemical waves traveling through the cytoplasm. Such waves ensure that cell division is properly coordinated in the large frog egg. Homogenized extracts can also spontaneously self-organize into various cellular spatial structures when mixing isolated components back together. For example, nuclei form around DNA and can replicate its genetic information. Moreover, microtubules are known to form a wide range of spatial patterns, such as a mitotic spindle, a critical structure to segregate the copied DNA between daughter cells. Altogether, a cytoplasmic extract is able to form a realistic pattern of cell-like structures that preserve the ability to divide when sperm is added.

Here, we will discuss some of our recent experimental and modeling efforts to understand how such waves and patterns form in the frog cytoplasm, and what their role is in organizing the cell division cycle.

Pulse reverberation with excitable microlasers

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We study the generation and regeneration of light pulses by vertical cavity surface emitting semiconductor micro-pillar lasers with saturable absorber. These devices are cheap to manufacture and easy to integrate into two-dimensional arrays, opening the door to many potential applications, such as optical communication, optical signal processing, and optical computation. Here, we focus the excitable behavior of an individual such laser with respect to an incoming pulse, regenerating it, but modifying its shape and timing.

We model successive pulse reverberation by a single laser with delayed optical feedback from a reflecting mirror, now corresponding to a sustained train of pulses. Alongside experimental findings of our collaborators, we present our analytical results on corresponding models with delayed feedback, in particular, a modified spin-flip model, as well as a rate-equation-type model with delayed feedback. Our analysis relies on the introduction of suitable co-moving coordinates in which the pulse train corresponds to a homoclinic orbit to a resting state of the system.

We conclude the talk with some recent results regarding the polarization-resolved pulsing dynamics of the device. We also discuss these results in light of dual-channel pulse propagation and neuro-mimetic applications of the device.

Nonlinear emergent dynamics of agent based models for urban mobility

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Traffic flow dynamics may manifest a very rich emergent nonlinear behaviour as consequence of the interactions between the vehicles and the complexity of the street network. Except of the traffic jams and traveling waves, many other complex nonlinear phenomena has been observed like stop and go waves and other spatio-temporal sustained oscillations and chaos. An important step towards the understanding of this complexity in large scale urban network is to study the emergent dynamics of traffic flow at networks intersections. Here, we propose and analyze the dynamics of an agent-based model, based on the so-called social force model, for simulating mobility of autonomous vehicles at intersections. The proposed model is able to replicate phenomena of collective behaviour that have been observed in real life situations and can be used as a realistic data generator for optimization purposes. Here, we will show some results for the case of crossing traffic flow without traffic lights. Particular attention is devoted to the variation of the vehicles density as this is a crucial parameter for the construction of the macroscopic fundamental diagram. In particular, we show that the emergent traffic flow dynamics exhibit multistabilty for a wide range of the density: except for the state of the free flow in both directions, other two steady states of stop and go-oscillating spatiotemporal patterns are found. The coarse-grained analysis is performed with the aid of the Equation-Free multiscale framework.

Critical intermittency in random interval maps

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Critical intermittency stands for a type of intermittent dynamics in iterated function systems, caused by an interplay of a superstable fixed point and a repelling fixed point. We consider critical intermittency for iterated function systems of interval maps and demonstrate the existence of a phase transition when varying probabilities, where the stationary measure changes between finite and infinite.

Impact of interlayer coupling type in a network of FitzHugh-Nagumo oscillators in the regimes of chimeras and solitary states

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We study numerically the spatiotemporal dynamics and synchronization of a heterogeneous two-layer multiplex network where each layer is represented by a ring of nonlocally coupled FitzHugh-Nagumo neurons in the oscillatory regime. When uncoupled, the layers can show chimera states, solitary states and combined structures (the coexistence of chimera and solitary states) depending on the values of the intralayer coupling parameters and initial conditions. We choose different spatiotemporal patterns in the coupled layers and systematically study synchronization between them when the interlayer coupling is introduced through either the fast (activator) or the slow (inhibitor) variable of the FitzHugh-Nagumo oscillators. Our results enable to uncover the competitive behavior between the solitary states and the chimeras in the transition to synchronous regime in the considered network.

Coevolution of cooperation and synchronization: Averting migration dilemma

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Synchronization, cooperation, and chaos are ubiquitous phenomena in nature. The emergence and sustenance of cooperation in a population composed of many subpopulations(demes) is a highly researched topic in the evolutionary game theory. In a population composed of many distinct groups of individuals playing the prisoner's dilemma game, there exists a migration dilemma: No cooperator would migrate to a group playing the prisoner's dilemma game lest it should be exploited by a defector; but unless the migration takes place, there is no chance of the entire population's cooperator fraction to increase. Employing a randomly rewired coupled map lattice of chaotic replicator maps, modeling replication-selection evolutionary game dynamics, we demonstrate that the cooperators—evolving in synchrony—overcome the migration dilemma to proliferate across the population when altruism is mildly incentivized making few of the demes play the leader game. The replicator map considered is capable of showing a variety of evolutionary outcomes, like convergent (fixed point) outcomes and nonconvergent (periodic and chaotic) outcomes. Furthermore, this coupled network of the replicator maps undergoes the phenomenon of amplitude death leading to non-oscillatory stable synchronized states. We specifically explore the effect of (i) the nature of coupling that models migration between the maps, (ii) the heterogenous demes (in the sense that not all the demes have same game being played by the individuals), (iii) the degree of the network, and (iv) the cost associated with the migration. In the course of investigation, we are intrigued by the effectiveness of the random migration in sustaining a uniform cooperator fraction across a population irrespective of the details of the replicator dynamics and the interaction among the demes. This work enlightens on the emergence of cooperation through random migration and synchronization.

Coupled behavior of oscillators under asymmetric forcing

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Oscillatory instabilities, which manifest themselves as large-amplitude periodic oscillations, are detrimental to various systems such as aeroacoustics, thermoacoustics, and civil structures such as bridges. Mutual coupling and external forcing are two schemes that have attracted wide attention in attempts to quench such instabilities. However, the simultaneous utilization of these coupling schemes in experimental setups has seldom been studied. In the present study, using experiments and theoretical modeling, we investigate the dynamics of two identical and nonidentical thermoacoustic oscillators simultaneously subjected to mutual coupling and asymmetric external forcing. We use a horizontal Rijke tube which is a prototypical thermoacoustic oscillator. Similar to existing studies, we observe amplitude (and partial amplitude) death in coupled Rijke tubes and asynchronous quenching in an externally forced single Rijke tube. When the two methods are applied simultaneously to a system of two coupled identical Rijke tubes, due to the complementary effect of amplitude death and asynchronous quenching, we observe a larger parametric region of oscillation quenching. This region of oscillation quenching is more extensive than when the two mechanisms are utilized individually. However, when a system of coupled nonidentical Rijke tubes is asymmetrically forced, the effect of forcing on attaining synchronization and quenching of oscillations in the Rijke tube that is not directly forced is insignificant. Finally, using a reduced-order theoretical model, we couple two Rijke tubes using dissipative and time-delay coupling and capture the experimental results qualitatively. Our results show the advantage of combining the two strategies of controlling oscillatory instabilities, which opens prospects for further studies in real-life systems.

Controlling nonlinear wave patterns in Marangoni convection

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A linear feedback control is known to be efficient for suppression of instabilities caused by infinitesimally small disturbances. However, it is not sufficient in the case of an instability with respect to finite-amplitude disturbances, which is characteristic for an inverse Hopf bifurcation. We investigate the effect of a nonlinear feedback control on the nonlinear development of a longwave oscillatory Marangoni instability in a thin viscous film heated from below. It is shown that a quadratic feedback control allows to replace a subcritical bifurcation by a supercritical one for traveling roll patterns. Also, it makes it possible to change the nonlinear interaction between disturbances with different wave-vectors in such a way that additional patterns become stable (e.g., traveling or standing squares and rectangles, and alternating roll patterns). A bistability between patterns of different spatial structures (e.g., traveling rolls and standing squares, or traveling rolls and alternating rolls) can be created.

Representing and characterizing complex dynamics by state-transition networks

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State-transition networks (STN) allow for a powerful representation and visualization of the dynamics of various complex systems with discrete states. Dynamical systems characterized by continuous time and phase space can also be mapped to STNs by sampling properly both space and time. Inspired by the Lyapunov exponents well known for chaos theory, here we introduce a novel network measure for STNs, together with an algorithm for converting multivariate time-series to sate-transition networks [1]. This novel measure is able to reflect the dynamical behavior of the underlying dynamical system, furthermore, unlike the traditional network measures, it may be used to predict upcoming crisis-type bifurcations when changing the control parameters. We explore the measure's properties by analytical and numerical results based on a theoretical model and demonstrate its applicability on the STN counterparts of the Henon map and the Lorenz system.

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Reduced-order models for coupled dynamical systems: data-driven and the Koopman Operator

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Providing efficient and accurate parametrizations for model reduction is a key goal in many areas of science and technology. Here we present a strong link between data-driven and theoretical approaches to achieving this goal. Formal perturbation expansions of the Koopman operator allow us to derive general stochastic parametrizations of weakly coupled dynamical systems. Such parametrizations yield a set of stochastic integro-differential equations with explicit noise and memory kernel formulas to describe the effects of unresolved variables. We show that the perturbation expansions involved need not be truncated when the coupling is additive. The unwieldy integro-differential equations can be recast as a simpler multilevel Markovian model, and we establish an intuitive connection with a generalized Langevin equation. This connection helps setting up a parallelism between the top-down, equations-based methodology herein and the well-established empirical model reduction (EMR) methodology that has been shown to provide efficient dynamical closures to partially observed systems. Hence, our findings support, on the one hand, the physical basis and robustness of the EMR methodology and, on the other hand, illustrate the practical relevance of the perturbative expansion used for deriving the parametrizations.

Partial relay synchronization in multiplex networks

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Relay synchronization is a dynamical phenomenon occurring in various complex networks and is characterized by the synchronization of remote parts of the network due to their interaction via a relay. This phenomenon has been observed in neural networks, lasers, and electronic circuits. In multilayer networks, distant layers that are not connected directly can synchronize due to signal propagation via relay layers. We study the influence of time delay in the inter-layer coupling on the partial synchronization of chimera states, complex patterns of coexisting coherent and incoherent domains. We demonstrate that three-layer structure of the network allows for synchronization of coherent domains of chimera state in the first layer with its counterpart in the third layer, whereas the incoherent domains are desynchronized. By introducing topological inhomogeneities in the layer and dilution between the layers, we study its influence on the remote synchronization in outer layers. Our results can be applied for secure communication and modelling of neuronal dynamics.

Geometric invariance of determining and resonating centers: Odd- and any-number limitations of Pyragas control

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Time-delayed feedback control using the Pyragas method is an important tool for the stabilization of equilibria and periodic orbits. However, the time delay generates an infinite dimensional system and consequently, general results on the controllability are rare and sometimes unclear. In this talk, we clarify the confusion in the literature on the odd-number limitation by deriving a fundamental observation on the invariance of the geometric multiplicity of the trivial Floquet multiplier and its resonating counterparts. From this geometric invariance, several odd- and any-number limitations follow (almost) immediately. This is joint work with Babette de Wolff (Freie Universität Berlin).

Low regularity integrators for non smooth phenomena

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Linear problems and smooth solutions are nowadays well understood, a reliable description of ‘non-smooth’ phenomena remains one of the most challenging open problems in computational mathematics. Nevertheless, ‘non-smooth phenomena’ play a fundamental role in modern physical modeling (e.g., blow-up phenomena, turbulences, high frequencies, low dispersion limits, etc.) which makes it an essential task to find suitable numerical schemes. In this talk I present a new class of low regularity integrators. The key idea in the construction of the new schemes lies in embedding the underlying oscillatory structure of the PDE into the numerical discretisation, addressing the fundamental question: How and to what extent can we reproduce the qualitative behavior of partial differential equations in a finite (discretized) world?

Bifurcation mechanisms behind solitary states in neural networks

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Networks of coupled identical oscillators are known to exhibit a variety of partial synchronization patterns. Among them are solitary states in which all but a few oscillators are synchronized in phase. Solitary states have been studied for nonlocally coupled networks with [1] and without delay [2], and multilayer networks [3, 4, 5]. In this work, we investigate the occurrence of such solitary states in globally coupled ensembles of FitzHugh-Nagumo oscillators. By restricting the system to a single solitary oscillator and applying the thermodynamic limit, the system can be reduced to a master-slave configuration in which the solitary node acts as a probe oscillator in the mean-field of the synchronized bulk. With this, we are able to show that solitary states are generated via a fold bifurcation on a branch originating in the symmetry breaking bifurcation of the homogeneous steady state. We show that these states undergo a period doubling cascade leading to a chaotic behavior of the solitary oscillator. Allowing more than one node to deviate from the synchronized bulk leads to intriguing patterns of non-identical behavior in the solitary cluster.

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Quenched limit theorems for expanding on average cocycles

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I will present a generalization of the spectral method to obtain quenched limit theorems for random systems that cover smooth or piecewise monotone expanding on average cocycles. It is based on the introduction of suitable adapted norms, and a scaling condition for the observable. It is a joint work with Davor Dragicevic.

Moment-driven predictive control of mean-field collective dynamics

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The study of collective behaviour phenomena from a multiscale modelling perspective has seen an increased level of activity over the last years. Classical examples in socio-economy, biology and robotics are given by self-propelled particles that interact according to a nonlinear model encoding various social rules as for example attraction, repulsion and alignment. Of particular interest for control design purposes is understanding the impact of control inputs in such complex systems and the study of mean-field control approaches where the control law obtain formal independence on the number of interacting agents. The construction of computational methods for mean-field optimal control is a challenging problem due to the nonlocality and nonlinearity arising from the dynamics. Furthermore, depending on the associated cost to be minimized, non-smooth and/or non-convex optimization problems might also arise. In order to circumvent these difficulties we propose a linearization-based approach for the computation of sub-optimal feedback laws obtained from the solution of differential matrix Riccati equations. Quantification of dynamic performance of such control laws leads to theoretical estimates on suitable linearization points of the nonlinear dynamics. Subsequently, the feedback laws are embedded into nonlinear model predictive control framework where the control is updated adaptively in time according to dynamic information on moments of linear mean-field dynamics. The performance and robustness of the proposed methodology is assessed through different numerical experiments in collective dynamics.

Manipulation of Temporal Localized Structures in a VECSEL With Optical Feedback

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We analyze both theoretically and experimentally the impact of optical feedback on the dynamics of external-cavity mode-locked semiconductor lasers (VECSELs) operated in the long cavity regime. In particular, by choosing certain ratios between the cavity round-trip time and the feedback delay, we show that feedback acts as a solution discriminator that either reinforces or hinders the appearance of one of the multiple harmonic arrangements of temporal localized structures. For the theoretical modeling, the delayed differential equation model of A. Vladimirov and D. Turaev (Phys. Rev. A 72, 033808 (2005)) is extended by a term describing the optical feedback. For the experimental realization, the gain medium consisting in 6 quantum wells embedded between a bottom totally reflective Bragg mirror and a top partially reflective Bragg mirror (1⁄2 VCSEL) was considered; the 1⁄2 VCSEL was then placed in an external cavity that was closed by a fast semiconductor saturable absorber mirror (SESAM) to operate the laser in the passive mode-locked regime. In the absence of the optical feedback such a laser can generate so-called harmonic mode-locked solutions. The optical feedback induces that each pulse is followed by a train of small copies of itself. The size and position of this echo can be controlled via the feedback rate and the delay time, respectively. When an echo is placed close to the leading edge of another pulse, the pulse experiences less amplification by the gain medium as it is already depleted by the echo. This interaction can lead to the destruction of the main pulse. In consequence, the system settles on a solution where pulses and echos are well-separated and thus, do not interact. In the further steps, a detailed bifurcation analysis is conducted where the influence of the position of the echo is investigated.

Dynamics and control of loop reactors

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In loop reactors the system is composed of several reactor units that are organized in a loop and the feeding takes place at one of several ports with switching of the feed port. In its simplest operation a pulse is formed and rotates around it, producing high temperatures which enable combustion of dilute streams. A limiting model with infinite number of units was derived. Rotating pulses, steady in a moving coordinate, emerge in both models when the switching to front propagation velocities 1. But this behavior exists over a narrow domain. Simulations were conducted with generic first order Arrhenius kinetics. Experimental observations are reviewed. Outside the narrow frozen rotating pattern domain the system may exhibit multi- or quasi-periodic operation separated by domains of inactive reaction. The bifurcation set incorporates many 'finger'-like domains of complex frequency-locked solutions that allow to extend the operation domain with higher feed temperatures. Control is necessary to attain stable simple rotating frozen pattern within the narrow domains of active operation. Various tested control approaches are reviewed. Actual implementation of combustion in LR will involve several reactants of different ignition temperatures. Design and control should be aimed at producing locked fronts and avoid extinction of slower reactions.

Vortex Shedding in Atomic Superfluid Gases

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The wake behind a moving object is a classic problem in fluid dynamics and it is well known that a transition from laminar to turbulent flow universally occurs in a viscous classical fluid as the Reynolds number increases. An interesting situation arises in a superfluid where zero viscosity disallows the Reynolds number and quantized circulation precludes continuous vorticity. When a superfluid flows past a large obstacle, the nucleation of quantized vortices occurs above a certain critical velocity, giving rise to drag and dissipation in the superfluid. The details of the vortex nucleation process and its relation to the microscopic modes of excitation remain as open questions in the study of dissipative superfluid dynamics. In this talk, I will present our vortex-shedding experiments with various atomic superfluid gases. Highly oblate large atomic samples were prepared and perturbed by translating a repulsive optical obstacle formed by a focused laser beam, and their responses in terms of vortex nucleation were investigated for various sweeping conditions. With weakly interacting atomic Bose-Einstein condensates, we observed a regular-to-turbulent transition of vortex shedding pattern as the obstacle velocity increases, resembling the universal behavior of classical fluids. In the experiments with strongly interacting atomic Fermi gases, we investigated the critical vortex shedding across the BEC-BCS crossover and observed a qualitative change of the dependence of the critical velocity, which is attributed to the participation of pair breaking in the vortex shedding dynamics. Finally, I will discuss our extension to a spinor superfluid with magnetic obstacles, where the interplay of mass and spin superfluidities leads to nucleation of new defects.

Numerical Solution of Nonlinear PDEs with Extreme Learning Machines

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We use a class of machine learning the so-called Extreme Learning Machines to numerically solve nonlinear partial differential equations (PDEs). For our demonstrations, we study two benchmark problems, namely (a) the one-dimensional viscous Burgers and, (b) the one- and two-dimensional Bratu PDEs. We also show how one can expolit the proposed methodology to construct bifurcation diagrams past limit points. The numerical efficiency of the proposed numerical machine-learning scheme is compared against central finite differences (FD) and Finite-element (FEM) methods. We show that the proposed ELM outperforms FD and importantly FEM for medium to large sized grids.

Change of criticality in a turbulent annular combustor

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The present study experimentally investigates the criticality of bifurcation leading to the state of thermoacoustic instability (TAI) in a turbulent annular combustor. Annular combustors are typically used in gas turbine and aircraft engines to generate thrust for propulsion. These combustors are prone to the occurrence of ruinously large-amplitude pressure oscillations resulting from positive feedback between the acoustic pressure oscillations and the heat release rate fluctuations of the flames. The lab-scale combustor consists of sixteen premixed swirl-stabilized flames arranged around an annulus. We demonstrate that the criticality of Hopf bifurcations is decided by the stabilizing or destabilizing nature of the dominant nonlinearities in the system when the control parameters such as flow rate and equivalence ratio are varied. We observe different states with distinct dynamics when a control parameter is varied. These dynamical states include the states of combustion noise (CN), intermittency (INT), low-amplitude TAI (LA-TAI), high-amplitude TAI (HA-TAI), and mixed-mode oscillations (MMO). We then discuss the global and local flame dynamics associated with the different dynamical states. Upon varying a control parameter, we find that the flame structure changes from an incoherent structure to a well-defined ring-like structure. We compare the local flame behavior by quantifying the degree of synchronization among the flames during different dynamical states using the Kuramoto order parameter. We find a transition from partially synchronized response of the flames during INT to weakly synchronized during LA-TAI, followed by weakly synchronized and perfectly synchronized for the duration of low- and high-amplitude oscillations in MMO, and perfectly synchronized during HA-TAI. We also develop a minimal phenomenological model containing higher-order nonlinearities that can capture the different criticalities of bifurcation as observed in the experiments.

Double-diffusive effects in the local instabilities of an elliptical vortex

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S. Singh and M. Mathur

Small-scale instabilities, which are local compared to the systems they exist in, play an instrumental role in understanding the mechanisms that lead to complex and often three-dimensional flow features. Vortices, for example, are ubiquitous in a turbulent flow and understanding their instabilities helps in a dynamical understanding of turbulence. A local stability approach, which calculates the inviscid evolution of relatively short-wavelength perturbations on a given base flow, has been instrumental in understanding various instabilities in vortical flows. In this study, we explore the effects of Schmidt number (Sc), which is the ratio between momentum and density diffusion coefficients, on the small-scale instabilities in an elliptical vortex with a stable stratification along its vortical axis. While the momentum and density diffusion coefficients are individually assumed to be small, their ratio Sc is allowed to be of arbitrary magnitude. The inviscid elliptical instability gets greatly modified due to the presence of a stable stratification. For Sc = 1, diffusion is shown to serve only as a suppressant of existing diffusion-free instabilities. We discover, however, that due to the presence of a stable stratification and a non-unity Sc, the vortex can be unstable in regimes which are stable based on a diffusion-free analysis. We characterize these non-unity Sc instabilities in detail, study how their growth rates depend on various base flow and perturbation parameters, and explore their potential connections with the diffusion-free instabilities

Strategies for controlling infectious disease dynamics

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This talk will review some recent results on the control of infection dynamics, for SIR as well as models that incorporate social distancing and other non-pharmaceutical interventions. Topics include formulas for optimizing the timing of fixed-length "lockdowns", a theoretical study of the dynamics of adaptive controllers that represent a population's perception of contagion, and models with fluxes among isolated compartments that are controlled by isolation mandates. Parts of this work are joint with Jim Greene, Jana Gevertz, Muhammad Al-Radhawi, Mahdiar Sadeghi, and Cynthia Hixahuary Sanchez Tapia (J. Theoretical Biology, 2020; Annual Reviews in Control, 2021, IEEE Control Systems Letters, 2021; and paper under review).

Tuning the richness of dynamical patterns in living neuronal networks through neuroengineering

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Living neuronal networks grown in culture offer a unique platform to understand collective behavior in neuronal circuits. The neurons' arrangement and connections can be dictated using neuroengineering tools, and therefore one can explore the impact of structural traits on dynamics. Specifically, in our laboratory we observed that neurons grown as two-dimensional networks in a flat surface exhibit an all-or-none synchronous behavior that is grounded on the capacity of any neuron to connect with any other. By arranging neurons in modules, imprinting obstacles in the substrate, or by growing the neurons in a three-dimensional environment, we observed that the activity may substantially change to a much richer repertoire. In the talk we will describe our experiments together with simulations that help explaining the experimental observations. We will also discuss the ingredients that are needed, in the context of connectivity and neuronal dynamics, to switch between synchronous and patterned dynamics.

Deep brain stimulation for movement disorder treatment: Exploring frequency-dependent efficacy in a computational network model

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A large scale computational model of the basal ganglia (BG) network and thalamus (THA) is proposed to describe movement disorder including deep brain stimulation (DBS). The model of this complex network considers three areas of the basal ganglia region: the subthalamic nucleus (STN) as target area of DBS, globus pallidus, both pars externa and pars interna (GPe-GPi), and the thalamus. Parkinsonian conditions are simulated by assuming reduced dopaminergic input and corresponding pronounced inhibitory or disinhibited projections to GPe and GPi. Macroscopic quantities can be derived which correlate closely to thalamic responses and hence motor programme fidelity. It can be demonstrated that depending on different levels of striatal projections to the GPe and GPi, the dynamics of these macroscopic quantities switch from normal conditions to parkinsonian. Simulating DBS on the STN affects the dynamics of the entire network, increasing the thalamic activity to levels close to normal, while differing from both normal and parkinsonian dynamics. Using the mentioned macroscopic quantities, the model proposes optimal DBS frequency ranges above 130 Hz.

Stochastic Analysis of Ensemble-based Kalman-type filters

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Consider the problem of estimating a Markovian signal observed with independent noise in continuous time. I will discuss two classes of ensemble-based filtering algorithms that have been proposed in the literature for the numerical approximation of the associated conditional distribution and discuss their asymptotic behavior in the infinite ensemble limit in terms of limiting mean-field processes on the level of the ensemble members and corresponding propagation of chaos results. I will also identify stochastic partial differential equations driving the distribution of the mean-field processes and perform a comparison with the Kushner-Stratonovich equation.

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Optimal renormalization of multi-scale systems

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While model order reduction is a promising approach in dealing with multi-scale time-dependent systems that are too large or too expensive to simulate for long times, the resulting reduced order models can suffer from instabilities. We have recently developed a time-dependent renormalization approach to stabilize such reduced models. In the current work, we extend this framework by introducing a parameter that controls the time-decay of the memory of such models and optimally select this parameter based on limited fully resolved simulations. First, we demonstrate our framework on the inviscid Burgers equation whose solution develops a finite-time singularity. Our renormalized reduced order models are stable and accurate for long times while using for their calibration only data from a full order simulation before the occurrence of the singularity. Furthermore, we apply this framework to the 3D Euler equations of incompressible fluid flow, where the problem of finite-time singularity formation is still open and where brute force simulation is only feasible for short times. Our approach allows us to obtain a perturbatively renormalizable model which is stable for long times and includes all the complex effects present in the 3D Euler dynamics. We find that, in each application, the renormalization coefficients display algebraic decay with increasing resolution, and that the parameter which controls the time-decay of the memory is problem-dependent.

Relay and complete sinchronization in heterogeneous multiplex networks of discrete maps

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In the present work we study relay and complete synchronization in a heterogeneous three-layer network of chaotic maps. The system under study includes an intermediate (relay) layer and two outer (layers) which are not directly coupled but interact via the relay layer. All the three layers are represented by rings of nonlocally coupled discrete-time oscillators but the individual dynamics of the relay layer elements is completely different from that of the outer layers. We consider the cases when the individual elements of the central layer and of the outer layers are described by Lozi maps and Henon maps, respectively, and vice versa. This enables one to observe various types of spatiotemporal structures, such as solitary states, amplitude and phase chimeras, and a solitary state chimera, when the subnetworks are uncoupled. In our work we explore for the first time the relay synchronization of the above mentioned structures in a heterogeneous multiplex network and analyze the role of the relay layer structure in the resulted synchronous patterns. We also reveal regimes of complete synchronization for the chimera structures and solitary states in all the three layers. The results are illustrated by regime diagrams in the "inter-layer coupling - intra-layer coupling of the relay layer" parameter planes.

Physical deep learning based on dynamical systems

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A central topic in recent artificial intelligence technologies is deep learning, which can be regarded as a kind of multilayer feedforward networks. An essence of deep learning is the information propagation through the layers, suggesting a direct connection between deep neural networks and dynamical systems, in the sense that the information propagation is explicitly modeled by the time-evolution of dynamical systems. Here, we present a pattern recognition based on optimal control of continuous-time dynamical systems [1]. The learning is based on the adjoint method to optimally control dynamical systems, and the deep (virtual) network structures based on the time evolution of the systems can be used for processing input information. As a key example, we apply the dynamics-based recognition approach to an optoelectronic delay system, and show that the use of the delay system allows for image recognition and nonlinear classifications, with only a few control signals, in contrast to conventional multilayer neural networks which require training of the huge numbers of weight parameters. The proposed approach enables to gain an insight onto mechanisms of deep network processing in the framework of an optimal control problem and opens a novel pathway to realize a physical computing hardware.

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Effect of recording length on the extraction of the photoplethysmogram dynamical characteristics by recurrence quantification analysis.

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A human photoplethysmogram is one of the biological signals used in clinical settings and wearable devices for heart rate, oxygen saturation, and blood pressure estimations. Contour and spectral analysis are commonly used for the photoplethysmogram analysis, but since the photoplethysmogram is a chaotic signal, methods of nonlinear time series analysis including recurrence quantification analysis may significantly contribute to advanced health monitoring applications. However, the application of recurrence quantification analysis for health monitoring purposes may require the usage of well-recorded signals. In practical cases, photoplethysmogram often can be recorded well only during a short time. Data length has a significant impact on the applicability of nonlinear time series analysis in general and on the recurrence quantification analysis in particular. Therefore, in this study reliability of dynamical characteristics extraction by recurrence quantification analysis was investigated in relation to the photoplethysmogram recording length.

Exact neural mass model for synaptic-based working memory

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A synaptic theory of Working Memory (WM) has been developed in the last decade as a possible alternative to the persistent spiking paradigm. In this context, we have developed a neural mass model able to reproduce exactly the dynamics of heterogeneous spiking neural networks encompassing realistic cellular mechanisms for short-term synaptic plasticity. This population model reproduces the macroscopic dynamics of the network in terms of the firing rate and the mean membrane potential. The latter quantity allows us to gain insight of the Local Field Potential and electroencephalographic signals measured during WM tasks to characterize the brain activity. More specifically synaptic facilitation and depression integrate each other to efficiently mimic WM operations via either synaptic reactivation or persistent activity. Memory access and loading are related to stimulus-locked transient oscillations followed by a steady-state activity in the $\beta - \gamma$ band, thus resembling what is observed in the cortex during vibrotactile stimuli in humans and object recognition in monkeys. Memory juggling and competition emerge already by loading only two items. However more items can be stored in WM by considering neural architectures composed of multiple excitatory populations and a common inhibitory pool. Memory capacity depends strongly on the presentation rate of the items and it maximizes for an optimal frequency range. In particular we provide an analytic expression for the maximal memory capacity. Furthermore, the mean membrane potential turns out to be a suitable proxy to measure the memory load, analogously to event driven potentials in experiments on humans. Finally we show that the γ power increases with the number of loaded items, as reported in many experiments, while θ and β power reveal non monotonic behaviours. In particular, β and γ rhythms are crucially sustained by the inhibitory activity, while the θ rhythm is controlled by excitatory synapses.

Bifurcation analysis of a density oscillator using two-dimensional hydrodynamic simulation

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N. Takeda, H. Ito and H. Kitahata

A density oscillator is an example of limit-cycle oscillators in hydrodynamic systems. The system consists of two different-density fluids put in two fixed containers. The inner and outer containers are for the higher- and lower-density fluids, respectively. The small hole at the bottom wall of the inner container connects the two fluids. In this system, the upstream of the lower-density fluid and the downstream of the higher-density fluid alternately occur through the hole in appropriate conditions. Owing to the simple setup, a density oscillator has been investigated mainly in experiments. In the previous studies, it has been reported that a density oscillator shows typical characteristics of a limit-cycle oscillation such as orbital stability and synchronization among several oscillators. Our recent experiment suggested that the density oscillator shows a supercritical Hopf bifurcation between the resting and oscillatory states depending on the density difference between the two fluids (H. Ito, T. Itasaka, N. Takeda, and H. Kitahata, EPL (2020)). However, we could not definitely identify the bifurcation class only from the experimental results because the measurement of a small-amplitude oscillation around a bifurcation point suffered from relatively large error. Therefore, we performed two-dimensional hydrodynamic simulations with a simple model and reproduced the oscillatory flow observed in experiments. As the density difference is increased as a bifurcation parameter, a damped oscillation changes to a limit-cycle oscillation through a supercritical Hopf bifurcation. We determined the critical density difference at the bifurcation point and confirmed that the period of the oscillation remains finite even around the bifurcation point (N. Takeda, N. Kurata, H. Ito, and H. Kitahata, Phys. Rev. E (2020)).

Structure-preserving Approximate Bayesian Computation for complex stochastic models

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Approximate Bayesian Computation (ABC) method has become one of the major tools for parameter inference in complex mathematical models in the last decade. The method is based on the idea of deriving an approximate posterior density aiming to target the true (unavailable) posterior by running massive simulations from the model for different parameters to replace the intractable likelihood, choosing then those parameters whose simulations are good matches to the observed data. When applying ABC to stochastic models, the derivation of effective summary statistics and proper distances is particularly challenging, since simulations from the model under the same parameter configuration result in different output. Moreover, since exact simulation from complex stochastic models is rarely possible, reliable numerical methods need to be applied. In this talk, we show how to use the underlying structural properties of the model to construct specific ABC summaries that are less sensitive to the intrinsic stochasticity of the model, and the importance of adopting reliable property-preserving numerical (splitting) schemes for the synthetic data generation. Indeed, the commonly used Euler-Maruyama scheme drastically fails even with very small stepsizes. The approach is illustrated on the broad class of partially observed Hamiltonian stochastic differential equations, both with simulated and with real electroencephalography (EEG) data. Reference: Buckwar, Tamborrino, Tubikanec. Statistics and computing 30 (3), 627-648, 2020

Complexity tuning by multiple delays

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The presence of time-delayed systems in vast ranges of topics from lasers to neuroscience, biology, etc., make them an appealing area of study. They are considered as a high-dimensional system capable of showing rich dynamical properties. They can be described by delayed differential equations(DDEs), in which the dynamical state of the current state highly depends on previous states. One of the most famously known DDE is Lang-Kobayashi equations which models a semiconductor laser with optical feedback.

In order to make use of this optical setup in practical applications, various techniques have been employed to increase the dynamical complexity. One of the proposed approaches to achieve this goal is to make dynamics dependent on multiple discrete delays rather than a single delay. Our numerical results show that increasing the number of delays can add complexity to the dynamics. However, in the limit of a large number of delays, transition to simpler dynamics such as limit cycle or stable fixed point occurs. To discover how complexity of the dynamic of this multi-delayed system is related to the number of delays, we measured the the Kolmogorov-Sinai entropy through the estimation of Lyapunov exponents.

Our discussion is then extended to first-order nonlinear time-delayed systems, such as the Mackey-Glass model. The numerical results show that increasing the number of delays is followed by abrupt drops in the measured complexity and at some point, the bifurcation diagram shows inverse period-doubling and eventually stable fixed point is seen. The interesting feature that we found in this multi-delayed system is that the density of the delays and the space between them determine the bifurcation structure.

Effects of social distancing and isolation on epidemic spreading modeled via dynamical density functional theory

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For preventing the spread of epidemics such as the coronavirus disease COVID-19, social distancing and the isolation of infected persons are crucial. However, existing reaction-diffusion equations for epidemic spreading are incapable of describing these effects. In this talk, we present an extended model for disease spread based on combining a susceptible-infected-recovered model with a dynamical density functional theory where social distancing and isolation of infected persons are explicitly taken into account [1]. We show that the model exhibits interesting transient phase separation associated with a reduction of the number of infections, and provides new insights into the control of pandemics. An extension of the model [2] allows for an investigation of adaptive containment strategies. Here, a variety of phases with different numbers of shutdowns and deaths are found, an effect that is of crucial importance for public health policy.

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Thin-film modelling of spreading biofilms and of drops of active liquids

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First, we consider thin-film models for spreading biofilms. After reviewing experiments [1,2] and modelling approaches [3] we establish the thin-film hydrodynamics for free surface films of mixtures where capillarity and wettability are incorporated. This passive model is then extended by bioactive terms like bacterial proliferation and biosurfactant production to obtain models for spreading biofilms [4,5]. We employ them to study (i) the arrest of biofilm spreading due to surface forces [4], and (ii) the emergence of fingering instabilities caused by biosurfactant production. As a result we distinguish four dynamical (morphological) modes of biofilm growth [5].

Second, we employ a related thin-film approach to model shallow drops of active liquid resting and moving on a solid substrate [6]. After introducing coupled evolution equations for film thickness and polarization profiles in the form of a gradient dynamics supplemented by active stresses and self-propulsion we discuss the behaviour of the model based on bifurcation analysis and time simulations. In particular, we show that defects in the polarization drastically influence the shape and motility of active droplets and observe a transition from resting to moving drops via the elimination of defects. Furthermore, we discuss drop splitting resulting from strong active contractile stresses.

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Controlling instabilities of falling liquid films

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We discuss control of the instabilities of fluid flows with free surfaces. The main scenario is a falling liquid film, with the goal of either stabilising a uniform film or driving the system towards a known travelling wave solution or stationary state. Possible controls include variable substrate topography, fluid injection and suction, or the imposition of external fields such as selective heating which would affect system properties such as surface tension or fluid viscosity. In principle, each of these controls could be delivered as steady patterning or in a time-dependent manner and so can deliver feedback control. We show that active feedback control, where inputs to the system are chosen in real time based on observations, is a far more potent tool than steady patterning if the aim is to manipulate the dynamics and stability of the system. However, the choice of feedback control strategy requires some knowledge of the underlying dynamics, and we focus particularly on whether control strategies developed based on analysis of simplified long-wave models remain effective when used in more complicated systems. Working in two spatial dimensions, we use a variety of long-wave models and Navier-Stokes simulations to explore feedback strategies when the control is actuated via same-fluid blowing and suction through the wall supporting the flow, or through selective localised heating. These mechanisms affect the dynamics in qualitatively different ways, and behave quite differently when considering robustness to model choice. We also discuss how feedback control schemes might be implemented more generally in experiments involving free surface flow.

Emergence of Chimera States in Hybrid Coupled Neuron Populations

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Here we study the emergence of chimera states, a recently reported phenomenon referring to the coexistence of synchronized and unsynchronized dynamical units, in a population of Morris-Lecar neurons which are coupled by both electrical and chemical synapses, constituting a hybrid synaptic architecture, as it occurs in the brain. Our model scheme consists of a nonlocal network where the nearest neighbour neurons are coupled by electrical synapses, while the synapses from more distant neurons are of the chemical type. We demonstrate that peculiar dynamical behaviours, including chimera state and traveling wave, exist in such a hybrid coupled neural system, and analyse how the relative abundance of chemical and electrical synapses affects the features of chimera and different synchrony states (i.e. incoherent, traveling wave and coherent) and the regions in the space of relevant parameters for their emergence. Additionally, we show that, when the relative population of chemical synapses increases further, a new intriguing chaotic dynamical behaviour appears above the region for chimera states. This is characterized by the coexistence of two distinct synchronized states with different amplitude, and an unsynchronized state, that we denote as a chaotic amplitude chimera. We also discuss about the computational implications of such state.

Testing Critical Slowing Down as a Bifurcation Indicator in a Low-dissipation Laser System

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A huge amount of research is devoted today to determine good indicators applicable on time series obtained from real systems that may anticipate a change in its behaviour [1,2]. A well-established indicator is the so-called "critical slowing down" (CSD), i.e. the divergence of the relaxation time of a dynamical system after a perturbation when the system is approaching a bifurcation [3]. In this contribution, we address the question whether CSD is always a good indicator of an incoming bifurcation in a system where a parameter is linearly changing in time. We answer to this questions by considering a laser system with a time swept pump where CSD appears only after the bifurcation has already occurred, hence when it is too late to reverse its behavioural change. Furthermore, we show experimentally that a perturbation in the accessible control parameter is unable to provide any indication, nor on the occurrence of CSD nor on the bifurcation crossing.

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Delay Induced Swarm Pattern Bifurcations in Mixed Reality Experiments

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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 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. The model is created based on statistical mechanics principles so it applies to large numbers of networked agents. A thorough bifurcation analysis has been carried out to explore parameter regions where various patterns occur. We extend this work to robotics applications by introducing a mixed-reality framework in which real and simulated robots communicate in real time creating the self-organized states predicted by the theory. 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 idealized (virtual) robots together in a swarm - the latter being well understood. As experiments progress more and more real robots can be connected to the swarm.

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On the interface of stochastic differential equations, structure-preserving numerics and statistical inference

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The interest in modelling dynamical real-world phenomena with stochastic differential equations (SDEs) has increased steadily in the last decades. For complex problems, explicit solutions are rarely available, and numerical approximations are required. This introduces an additional modelling step, and the numerical method can be viewed as the solution of a corresponding discrete dynamical system for a given time discretisation step. Its behaviour may deviate completely from that of the true solution, making it practically useless or very inefficient. The idea behind structure preservation is to guarantee that the solution of the discrete problem has the same (or similar) properties as the solution of the continuous model. In this talk, we address the importance of structure preservation when numerical methods are used within statistical inference tools. For example, numerical methods are used to generate synthetic data in simulation-based inference algorithms, or to approximate the transition density of the process within likelihood-based inference tools. The Euler-Maruyama discretisation or similar methods are often considered suitable for describing the underlying data. However, they may not obey the defining structural properties of the observable phenomenon. This may lead to ill-posedness of the estimation tool or make reliable inference impossible. We discuss these issues in the context of stochastic neuronal models, and construct structure-preserving numerical splitting methods.

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Double-diffusive convection via 2 by 2 matrices

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Convection due to competing or cooperating mechanisms, displays a variety of dynamical phenomena. One mechanism is usually a thermal gradient; typical examples of the second are rotation, a magnetic field, or a concentration gradient. The transition from conduction to convection is via a steady or a Hopf bifurcation; the point separating them is the best known codimension-two point. The steady bifurcation may be super or sub-critical, and the amplitude may undergo a qualitative transition from weak to strong.

All these features – linear and nonlinear – can be explained as manifestations of the behavior of the eigenvalues of a generic 2 x 2 matrix near the point where the eigenvalue branches intersect. For the stability problem, the eigenvalues have the conventional interpretation as growth rates, while for the nonlinear steady-state problems, they can be interpreted as the energy of steady states. Thus, there is a strong analogy between the stability problem and the bifurcation diagram.

Intelligent swarming and future entropy

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We implement "intelligent" swarming in systems of motile agents. These agents infer information about those states likely to be accessible to them in the future. They do this by (virtually) projecting themselves forward in time, together with all other agents. Their trajectories are conditional over reorientation moves that they may make and so we exhaustively enumerate over the decision trees that result. For each such path we identify an entropy associated with visual projections of the agent's environment (here, all other agents) onto retina-like sensors. Each agent then uses this information to decide whether to re-orientates itself in the present, so as to target the highest such entropy over future paths. Models that employ such an entropy over future states are shown to be similar to those that rely on crude count of non-degenerate states. We regard our model as a good candidate for a “bottom up” model of swarming: It does not directly encode cohesion or coalignment, rather those arise naturally. Furthermore, the principle of maximising the variety of possible states accessible in the future may have a deep connection with evolutionary fitness more generally. We examine the role of the future time horizon (the depth of the future decision-tree) and the number of visual sensors. New phenotypes emerge as the number of sensors increases. These involve the corralled motion of sub-swarms within a finite spatial region that is essentially immobile. These sub-swarms have a broad distribution of sizes, each having high local order (coalignment), but with low global order. We compare this with the dynamics of large animal collectives, e.g. flocks of starlings with $N > 10^5$ birds, that also show high local order with low global order.

Reconstructing Network Structures from Partial Measurements

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The dynamics of systems of interacting agents is determined by the structure of their coupling network. The knowledge of the latter is therefore highly desirable, for instance to develop efficient control schemes, to accurately predict the dynamics or to better understand inter-agent processes. In many important and interesting situations, the network structure is not known, however, and previous investigations have shown how it may be inferred from complete measurement time series, on each and every agent. These methods implicitly presuppose that, even though the network is not known, all its nodes are. A major shortcoming of theirs is that they cannot provide any reliable information, not even on partial network structures, as soon as some agents are unobservable. Here, we construct a novel method that determines network structures even when not all agents are measurable. We establish analytically and illustrate numerically that velocity signal correlators encode not only direct couplings, but also geodesic distances in the coupling network, within the subset of measurable agents. When dynamical data are accessible for all agents, our method is furthermore algorithmically more efficient than the traditional ones, because it does not rely on matrix inversion.

Vibrational energy distribution in plate excited with random white noise

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In Statistical Energy Analysis (SEA) and more generally in all statistical theories of sound and vibration, the establishment of diuse field in subsystems is one of the most important assumption. Diffuse field is a special state of vibration for which the vibrational energy is homogeneously and isotropically distributed. For subsystems excited with a random white noise, the vibration tends to become diffuse when the number of modes is large and the damping sufficiently light. However even under these conditions, the so-called coherent backscattering enhancement (CBE) observed for certain symmetric subsystems may impede diffusivity. In this study, CBE is observed numerically for various geometries of subsystem. Theoretical and numerical simulations are provided to support the discussion.

Ubiquity of collective irregular dynamics

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Collective Irregular Dynamics (CID) is a form of partial “synchronization". In contrast to other synchronized states, it is characterised by a complex dynamical structure. Irregular fluctuations persist in networks of arbitrary size: it is a collective phenomenon akin to a thermodynamic phase encountered in statistical mechanics. This regime emerges spontaneously in several recurrent networks of spiking neurons. We study CID in various models of spiking neurons: non-identical phase-oscillators globally coupled through delta-spikes, balanced random networks of identical leaky-integrate-and-fire models with sparse or massive connectivities, and phase oscillators with a suitable phase-response-curve in a balanced random network with finite pulse coupling.

We combine analytical and numerical studies, starting from the linear stability analysis of the synchronous and asynchronous regime, to include the Fourier analysis of the Kuramoto order parameter, the computation of various types of Lyapunov exponents, a microscopic study of the interspike intervals and a detailed finite-size scaling analysis. We can conclude that CID is a true thermodynamic phase, intrinsically different from the standard asynchronous regime. We go beyond the usual approach of delta-spikes and investigate also more realistic finite-widths pulses in terms of exponential spikes. CID is robust also in this more natural setup and we identify particularities present only for artificial delta-spikes.

Vibro-acoustic analysis of systems containing domain couplings based on the Gaussian Orthogonal Ensemble

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At high frequencies, the analysis of the response of structural and acoustic systems is challenging, due to the large sensitivity to spatial variations and the short wavelengths appearing at these frequencies, making deterministic element-based methods such as the finite element method very expensive. At these frequencies, stochastic energy-based methods like statistical energy analysis (SEA) are often employed. Although SEA is computationally very efficient, it has some shortcomings as the joint probability density function of the response is not available and the vibration fields cannot be retrieved as only the total energies are obtained. In this contribution, a nonparametric field-based approach is presented. The methodology uses a Monte Carlo simulation, in which each sample represents a realization of a diffuse field. This allows predicting the variance and probability density function of the response variables and accounting for additional parametric uncertainty without increasing the computational cost. The approach is computationally efficient as the natural frequencies and mode shapes of the random subsystems are directly drawn from universal probability distributions: the local eigenvalue spacings of the system components conform to the Gaussian Orthogonal Ensemble (GOE) and the mode shapes are zero-mean Gaussian random fields. The focus of this contribution is on domain coupling between structural and acoustic system components. Using mode shape components is computationally expensive, as they are needed over a fine interface mesh. Instead, the coupling is done through coupling matrices whose entries are computed from their probability density function, which can be calculated exactly. The method is illustrated with several case studies.

Ergodicity and the dynamics of human decision making

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People do not change easily. They seem irrationally fond of the status quo and need a great deal of convincing before changing habits, even when the change appears beneficial. For instance, to get people to change modes of transportation, policymakers and researchers have thought up a great deal of incentives. Unfortunately, these incentives do not always have the desired effect or sometimes even have the adverse impact.

Within the novel framework of Ergodicity Economics, it is possible to explains some of these failures by highlighting our overdependence on ensemble averages when designing incentives and judging the benefits of a modal shift. Indeed, when modelling human decision-making, ergodicity is often implicitly assumed. Consequently, ensemble averages judge the (ir)rationality of human decision-making. However, when we step away from this assumption, i.e., ensemble averages and time averages are no longer assumed to be equal, we can rationalize much of this seemingly irrational behaviour by looking at the time average of an individual in a dynamic and stochastic environment, instead of relying on the expected value of the process. Loss aversion, e.g., rather than being a compulsory drive to cling to what you already have, becomes a way of mitigating downside risk and eventual ruin. The status quo bias or the irrational hesitance towards change also makes sense in a non-ergodic world as uncertainty looms greater in a non-ergodic world than in an ergodic one.

In this contribution, we will use transportation data to demonstrate that, we can shift the dialogue regarding strategies for inducing behavioural change from one that focuses on idiosyncratic preferences and irrationalities to one that enhances the objective drivers of change. Instead of looking into personal reasons for not opting for sustainable mobility, we look at the determining factors objectively keeping us from change in a non-ergodic world.

Spatial and color hallucinations in a mathematical model of primary visual cortex

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We present a recent model [Song et al. 2019] of color perception unifying assimilation and contrast. This model, which relies on the notion of color opponency introduced by Hering, has been tuned to reproduce some nontrivial behaviors of the color shifts observed in experiments. Next, we perform equivariant bifurcation analysis, based on the properties of Wiener-Hopf operators, of this planar model to predict visual hallucinations. Numerical bifurcation analysis on GPU are provided to assess the global stability of the predicted visual hallucinations.

pattern formation on a finite disk

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The dynamics of the cubic-quintic Swift-Hohenberg equation over a finite disk with no-flux boundary conditions are studied. We predict the unstable modes of the trivial state using a linear stability analysis. These modes are followed via numerical continuation, revealing a great variety of spatially extended and spatially localized behaviors. Notably, we find solutions localized in the interior as well as solutions localized along the boundary or part of the boundary. Bifurcation diagrams summarizing these results and their stability properties are presented, linking the different solutions.

The findings of this study are likely relevant to nonlinear optics, combustion as well as convection.

Chaos on a saturable dimer

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In this talk we will discuss our recent results on the study of a nonlinear saturable dimer. Stationary and integrable properties of this system are well known; however, no much information is found in literature respect to a non-integrable regime where, for example, by periodically modulating the nonlinear coefficient a chaotic dynamics is observed. This observation strongly depends on the level of power in the system, where four different regimes are clearly defined. At the end, I will mention about a possible photonic application where information can be codified using the input power.

Short pulse solutions of time-delay laser models

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Delay differential equation model of NOLM-NALM mode-locked laser is developed that takes into account finite relaxation rate of the gain medium and asymmetric beam splitting at the entrance of the nonlinear mirror loop. Asymptotic linear stability analysis of the CW solutions performed in the limit of large delay indicates that in a class-B laser flip instability leading to a period doubling cascade and development of square-wave patterns can be suppressed by a short wavelength modulational instability. Numerically it is shown that the model demonstrates large windows of regular fundamental and harmonic mode-locked regimes with single and multiple pulses per cavity round trip time separated by domains of irregular pulsing. Asymptotic theory of the short mode-locked pulse interaction is discussed.

Climate response and climate tipping points: dynamical systems approaches

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The currently ongoing climate change and the debate about possible measures to be taken to limit the consequences of climate change, requires to know and understand the future response of the climate system to greenhouse gas emissions. The Equilibrium Climate Sensitivity (ECS) - defined as the equilibrium global surface temperature response to a doubling of CO_2 - is a key predictor of climate change and has been estimated from climate models, observational, historical and palaeoclimate data. However, its distribution (1.5 to 4.5 $^\circ$C) as reported in the last IPCC report remains relatively uncertain and has not changed much from the very first estimates. Even more worrying, the latest versions of the most complex Earth System models (CMIP6) suggest even higher estimates for ECS than previous model generations. This does not mean that climate system science has not advanced; the climate system shows internal variability on many timescales, is subject to non-stationary forcing and is most likely out of equilibrium with the changes in the radiative forcing. Slow and fast feedbacks complicate the interpretation of geological records as feedback strengths vary over time. In the geological past, the forcing timescales were different than at present, suggesting that the response may have behaved differently. Abrupt transitions associated with tipping elements in climate subsystems have occurred in the past and are likely to occur in the future. In this lecture I will review the progress made in the theoretical understanding of the climate sensitivity. I will introduce the *climate attractor* and discuss more general notions of ECS on the attractor that can be useful in understanding the response of a climate state to changes in radiative forcing. For example, different time scales in both forcing and response need to be taken into account, and the general underlying assumption of a time-scale separation should be carefully evaluated. The current ECS defines a linear response; however, a climate state close to a tipping point will have a degenerate linear response to perturbations, which can be associated with extreme values of the ECS.

Wavelength selection by interrupted coarsening in reaction–diffusion systems

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Intracellular pattern formation can be described by (nearly) mass-conserving reaction–diffusion systems. Of these, two-component mass-conserving reaction–diffusion systems are paradigmatic models, also used to describe for example precipitation patterns or granular media systems. We will discuss the implications of the conservation law and argue based on the phase-space structure of the the mass-conserving reaction–diffusion models that these generically show uninterrupted coarsening. Our theory clarifies that positive feedback in the mass transport between neighboring pattern domains drives this coarsening process. It implies a general coarsening criterion and allows to determine the coarsening law. We further use this understanding to explain wavelength selection due to weak source terms as the arrest of coarsening. This analysis will exemplify how the phase-space structure of pattern-forming systems may be used to study wavelength selection far from equilibrium.

Stability properties of temporal dissipative solitons in DDE systems

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Localized states are an universal phenomenon in spatially extended nonlinear systems. Recently, also temporally localized states have gained some attention, mainly driven by applications in various optical systems, where the dynamics of short optical pulses can be described by DDE models. We present a theory for such states, which appear as periodic solutions with a period close to the round trip time of the system. We study such solutions by using the singular limit of large delay. We derive a desingularized equation for the solution profiles, and study the corresponding Floquet spectrum for their stability. To this end, we derive an Evans function and discuss the analogies and differences to the classical theory for localized states in spatially extended systems.

Frequency cluster formation and slow oscillations in neural populations with plasticity

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We report the phenomenon of frequency clustering and discuss the mechanisms of their emergence in networks of adaptively coupled oscillators. The clustering leads to a splitting of a neural population into a few groups synchronized at different frequencies. In a network of Hodgkin-Huxley neurons with spike timing-dependent plasticity, in the regime of frequency clustering, the amplitude of the mean-field undergoes low-frequency modulations, which may contribute to the mechanism of the emergence of slow oscillations of neural activity observed in spectral power of local field potentials or electroencephalographic signals at high frequencies.

Nonlinear model reduction for slow-fast stochastic systems near manifolds

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We introduce a nonlinear stochastic model reduction technique for high-dimensional stochastic dynamical systems that have a low-dimensional invariant effective manifold with slow dynamics, and high-dimensional, large fast modes. Given only access to a black box simulator from which short bursts of simulation can be obtained, we estimate the invariant manifold, a process of the effective (stochastic) dynamics on it, and construct an efficient simulator thereof. These estimation steps can be performed on-the-fly, leading to efficient exploration of the effective state space, without losing consistency with the underlying dynamics. This construction enables fast and efficient simulation of paths of the effective dynamics, together with estimation of crucial features and observables of such dynamics, including the stationary distribution, identification of metastable states, and residence times and transition rates between them.

Spirographic motion in a vortex

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Non-spherical solid particles can display rich dynamics even in laminar flows and when the particle inertia is negligible. In particular, particles in shear flows have attracted a lot of attention in the literature. In such flows, periodic orbits are observed for axisymmetric particles, whereas chaotic dynamics can emerge as a consequence of Brownian fluctuations, the non-axisymmetry of the particles, or a time-dependent flow. The case of vortex flows has been less investigated, and the studies have mainly focused on point-like particles. Here, we consider the motion of an extended object that can experience the nonlinearity of a vortex. To this end, we investigate the dynamics of a rigid dumbbell, which consists of two beads connected by a rigid link. It is shown that the centre of mass of the dumbbell exhibits an inwards and outwards spiralling motion which results into spirographic trajectories around the centre of the vortex. More precisely, the motion of the centre of mass of the dumbbell is the superposition of a periodic oscillation in the radial direction and a revolution around the centre of the vortex which is slaved to the radial distance and the orientation of the dumbbell. The shape of the trajectories depends very strongly on the initial position and orientation. The dynamics is explained analytically by studying the fixed points and the periodic orbits of the system in phase space. The analytical results hold for any general vortex flow and are illustrated numerically for the Lamb-Oseen vortex.

Collisions of excitable solitons: Annihilation, crossover, and nucleation of pulses in a model describing intracellular actin waves

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Excitable pulses are among the most widespread dynamical patterns that occur in many different systems, ranging from biological cells to chemical reactions and ecological populations. Traditionally, the mutual annihilation of two colliding pulses is regarded as their prototypical signature. Using a model of intracellular actin waves and bifurcation theory about a T-point of periodic and homoclinic orbits in space, we show why colliding excitable pulses may exhibit soliton-like crossover and pulse nucleation if the system obeys a mass conservation constraint. In contrast to previous observations in models without mass conservation, these alternative collision scenarios are robustly observed over a wide range of parameters. As biological cells are inherently mass-conserved systems, our results provide a key concept to understand the ubiquitous occurrence of actin waves in cells, explaining why they are so common, and why their dynamics are robust and long-lived.

Instabilities in nonisothermal Taylor-Couette flows in radial electric fields

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In non-isothermal dielectric fluids subject to electric fields, the coupling between electric and temperature fields through the thermal variation of permittivity gives rise to an electrohydrodynamic force and can generate convective motion in fluids [see, e.g., Yoshikawa et al., 87, 043003, 2013]. The convection driven by this thermo-electrohydrodynamic effect is of importance in active control of heat and mass transport in small fluid systems, e.g., for manipulation of particles to modify locally their concentration [Kumar et al. Langmuir, 26(7), 5262-5272, 2010]. By the linear stability theory, we investigate instabilities provoked by the TEHD force in Taylor-Couette (TC) flow systems subject to radial temperature gradient and electric field. Different TC systems of different gap widths in different gravitational environments, i.e., in microgravity and on the Earth are considered. Depending on the radius ration of inner to outer cylinders and on the gravitational condition, different instabilities are observed. We elucidate the driving effects of different instabilities by an energetic analysis. We also examine effects of dielectric loss on the instabilities.

The visual cortex as a window into the brain and the world of large dynamical systems

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In the past several years, I have been involved in building a biologically realistic model of the monkey visual cortex. Work on the input layer of the primary visual cortex (V1) is now nearly complete, and I would like to share some of what I have learned with you. The model is a large structured network of small subsystems representing the dynamics of individual neurons. I plan to divide my time between the following two topics: (1) Local circuits, the dynamics of which I will describe in some detail, including an emergent rhythm detected all over the brain, and (2) dynamics across the cortical surface in an input layer of V1. I will discuss nonequilibrium steady states that arise in response to stationary stimuli, and how one might treat nonstationary inputs. This motivates, for general dynamical systems, the need (and some ideas) for going beyond SRB measures.

Theory of active phase separation for bacterial aggregates

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Aggregates of living cells are examples of active materials with unconventional material properties.

The rheological properties of cellular aggregates can, therefore, be markedly different from those exhibited by passive soft-matter systems. Motivated by colonies of Neisseria gonorrhoeae bacteria, we develop a continuum theory to study cellular aggregates formed by attractive pili-mediated intercellular interactions which generate active stresses in the system. The formation of cellular aggregates can be explained by an active phase separation concept, and the activity-induced viscoelastic properties of such aggregates are coupled with pili-mediated interactions. By studying the behavior of aggregates under oscillatory shear, the viscous and elastic moduli of the aggregates can be linked to the dynamics of the active interactions. Due to the turnover of pili, the aggregates exhibit a liquid-like behavior at large times and a strong shear-thinning effect under the large amplitude of oscillatory shear. Our theory provides an essential insight on how active intercellular forces may drive phase separation of cellular aggregates and govern their material properties, which, in the future, could be tested experimentally.

Taming spikecounts in a bursting neuron with self-induced stochastic resonance

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Noise is ubiquitous in neurons. Here we show noise can control the spike counts in bursts of the Hedgehog burster via the self-induced stochastic resonance (SISR) phenomenon. Through the distance matching condition, the critical transition positions on the slow manifolds can be predicted and the stochastic periodic orbits can be accordingly obtained. The critical transition positions on the slow manifold with non-monotonic potential difference exhibit a stair-like behavior, which can be also uncovered by the period of the stochastic periodic orbits. The noise-tuned bursting is more coherent within each stair while displays mixed-mode oscillations near the boundaries. Further increasing the noise strength could induce the slow variable trap phenomenon and larger noise allows more traps to be coexisted. The robustness of SISR underlies the generality of the above results.

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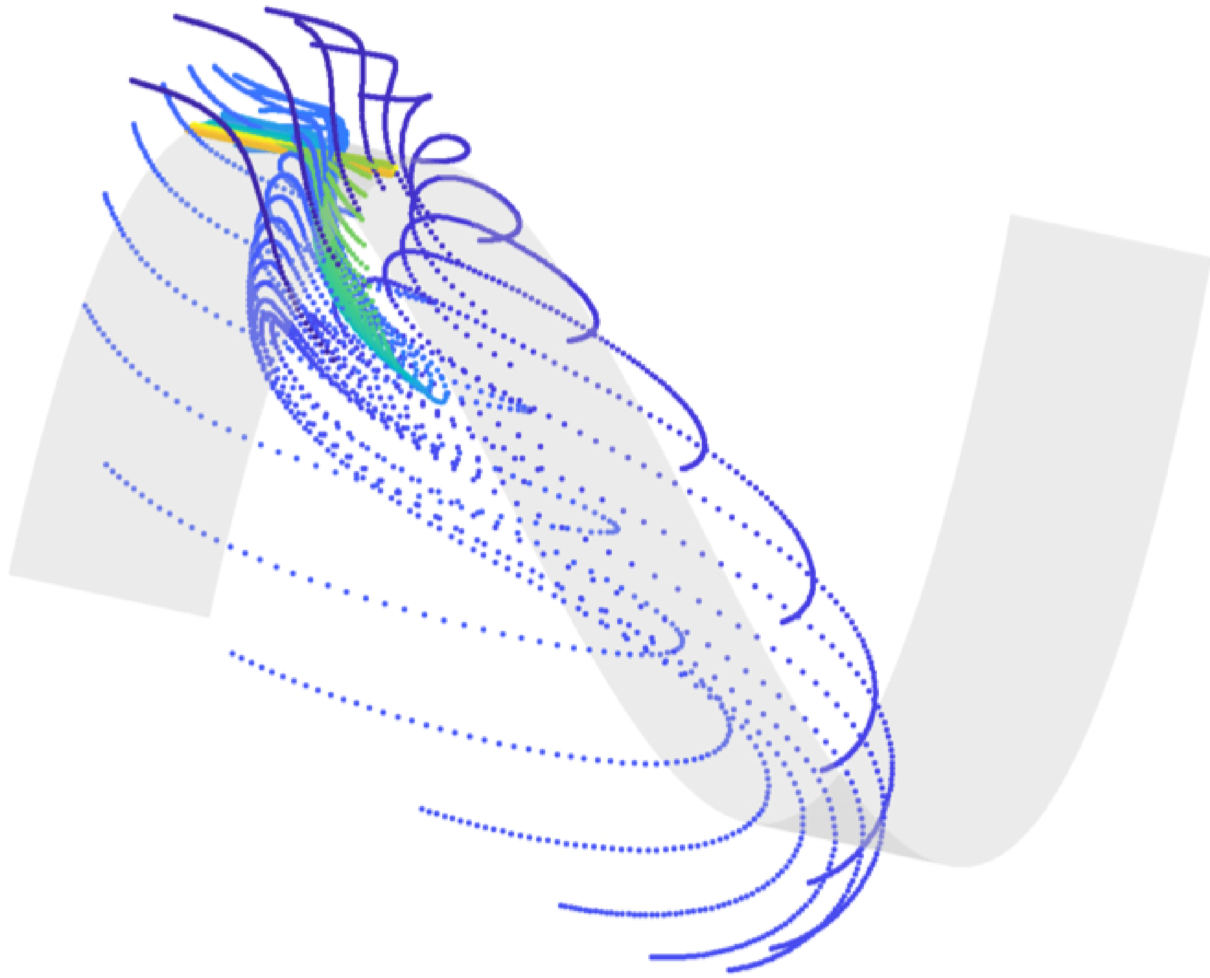

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