IP1

Some Geometrical and Physical Aspects of Morphogenesis

How is living matter organized in space and time during morphogenesis ? A comparative view across animal and plant species suggests that the answer may lie in reusing just a few geometric cellular principles and organ-sculpting motifs. Using examples, I will discuss the quantitative basis for three of these motifs: elongation, lumenization and folding.

L Mahadevan
Harvard University
lm@seas.harvard.edu

IP2

Pattern Formation in the Drylands: Vegetation Patterns in Mathematical Models and in Satellite Images of the Horn of Africa

An awe-inspiring example of spontaneous pattern formation appears in the distribution of vegetation in some dryland environments. Examples from Africa, Australia and the Americas reveal vegetation congregated in stripe-like bands, alternating with striking regularity with bands of bare soil. A typical length scale for such patterns is 100 m; they may be readily surveyed in Google Maps. The typical time scale for pattern evolution, however, is 100 years, so investigations of dynamics are a bit thwarted, with only a few early data points provided by aerial photographs from the 1950s. These ecosystems represent some of Earths most vulnerable under threats to desertification, and ecologists have suggested that the patterns, easily monitored by satellites, may tell us something about a regions possible stage of collapse. This is an attractive idea, especially to us pattern formation researchers who want to work on problems that have potential impact. My talk consists of two parts. In the first, I describe how one proposed early warning sign, related to vegetation pattern morphology, can be framed mathematically in terms of an equivariant bifurcation problem, and then probed by a systematic analysis of models. In the second, I turn to investigations of image data, focusing on our preliminary studies of vegetation patterns in the Horn of Africa. The goal of this presentation is to highlight the potential for models to be confronted by data, and vice versa.

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

IP3

Random Long Time Dynamics for Large Systems of Interacting Oscillators

A considerable amount of effort has been put into understanding large scale dynamics of interacting particles or, more generally, interacting "units" (like cells or individuals). This large scale limit, leading often to a partial differential equation, is in most cases taken under the assumption of finite time horizon. This of course raises the crucial issue of the relevance of long time dynamics for the limit PDE when dealing with the long time dynamics of the original system, which is made of a finite number of particles or units. This issue has been successfully tackled for stochastic systems (the large scale limit is in this case a law of large numbers) for the cases in which deviations from this limit can only be due to very rare events (Large Deviations). The net result is that the deviations from the limit behavior can be observed only on time scales that are huge (for example, the exponential of number of particles/units in the system). However, in several natural instances deviations happen on a much shorter time scale. After discussing this important issue and its practical relevance in a general framework, I will focus on mean field synchronization models for which 1. we can sharply trace the time scale of validity of the deterministic large scale PDE; 2. we can describe in detail what happens after this time scale. The talk is based on papers written by subsets of the following authors: Lorenzo Bertini, Eric Luçon, Christophe Poquet, & myself.

Giambattista Giacomin
Université Paris Diderot
giambattista.giacomin@univ-paris-diderot.fr

IP4

Computational Approach Elucidating the Mechanisms of Cardiovascular Diseases

Cardiovascular diseases such as aortic aneurysms and aortic dissections persist as life-threatening hazards. Patient-specific simulations are now common in biomedical engineering. Although they are extremely useful for grasping the flow/stress distributions and for patient-specific treatment planning, they remain insufficient to elucidate the general mechanisms of a targeted disease. Several mathematical viewpoints should play important roles in this context. For instance, we introduce a geometrical characterization of blood vessels, which vary widely among individuals. Differences in the vessel morphology can produce different flow characteristics, stress distributions, and ultimately different outcomes. Therefore, the characterization of the morphologies of these vessels poses an important clinical question. Through close collaboration with medical doctors, these analyses can yield greater understanding leading to better risk assessments.

Hiroshi Suito
Okayama University and
Tohoku University, Japan
suito@okayama-u.ac.jp

IP5

Dynamics, Mixing, and Coherence

Coherent regions in geophysical flows play fundamental roles by organising fluid flow and obstructing transport. For example, in the ocean, coherence impacts dynamics from global scales down to scales of at least tens of kilometres, and strongly influences the transportation of heat, salt, nutrients, phytoplankton, pollution, and garbage. I will describe some recent mathematical constructions, ranging across dynamical systems, probability, and geometry, which enable the accurate identification and tracking of such structures, and the quantification of associated mixing and transport properties. I will present case studies from a variety of geophysical settings.

Gary Froyland
UNSW Australia
g.froyland@unsw.edu.au

IP6

Stochastic Arnold Diffusion of Deterministic Sys-

tems

In 1964, V. Arnold constructed an example of a nearly integrable deterministicsystem exhibiting instabilities. In the 1970s, physicist B. Chirikov coined the term for this phenomenon Arnold diffusion, where diffusion refers to stochastic nature of instability. One of the most famous examples of stochastic instabilities for nearly integrable systems is dynamics of Asteroids in Kirkwood gaps in the Asteroid belt. They were discovered numerically by astronomer J. Wisdom. During the talk we describe a class of nearly integrable deterministic systems, where we prove stochastic diffusive behavior. Namely, we show that distributions given by deterministic evolution of certain random initial conditions weakly converge to a diffusion process. This result is conceptually different from known mathematical results, where existence of diffusing orbits is shown. This work is based on joint papers with O. Castejon, M. Guardia, J. Zhang, and K. Zhang.

Vadim Kaloshin
University of Maryland at College Park, USA and
ETH Zürich
vadim.kaloshin@gmail.com

IP7
Interactions, Deformations and Bifurcations of Singular Patterns

Singular patterns appear in multiscale systems. These systems exhibit the rich behavior of general systems, their singular nature provides a structure by which this may be understood. Moreover, many natural phenomena are modeled by such systems. I will discuss the strong cross-fertilization between applications and the development of mathematical theory. Unravelling the nature of patterns exhibited by specific chemical or ecological models goes hand in hand with uncovering novel generic destabilization mechanisms as the 'Hopf dance'. Understanding realistic patterns requires analytical descriptions of deformations, bifurcations and annihilation of interacting localized structures – from an ecological point of view preferably under varying (climatological) circumstances. Through this, mathematics may explain why desertification sometimes is a sudden catastrophic event, while it is a gradual process in other situations.

Arjen Doelman
Mathematisch Instituut
doelman@math.leidenuniv.nl

SP1
Juergen Moser Lecture - Emergent Behavior in Large Systems of Many Coupled Oscillators

Large systems of many coupled dynamical units are of crucial interest in a host of physical, biological and technological settings. Often the dynamical units that are coupled exhibit oscillatory behavior. The understanding and analysis of these large, complex systems offers many challenges. In this talk I will introduce this topic, give some examples, and describe a technique for analyzing a large class of problems of this type. The results I will discuss will reduce the complicated, high dimensional, microscopic dynamics of the full system to that or a low dimensional system governing the macroscopic evolution of certain 'order parameters'. This reduction is exact in the limit of large system size, i.e., N going to infinity, where N is the number of coupled units, and can be employed to discover and study all the macroscopic attractors and bifurcations of these systems.

Edward Ott
University of Maryland
Inst. for Research in Electronics and Applied Physics
edott@umd.edu

CP0
Mentoring Program

See session abstract.

Conference Participants
n/a
n/a

CP0
Student Icebreaker

On Saturday immediately before the opening reception, there will be an informal Student Icebreaker session. Through structured activities, the primary goal is for attendees to leave feeling comfortable about the meeting, and having made new connections to depend on as friendly faces during the conference. There is no additional cost, but in order to get a count on how many people to expect, we request that you register for this session when you register for the conference.

Chad M. Topaz
Dept. of Mathematics, Statistics, and Computer Science
Macalester College
ctopaz@macalester.edu

CP1
Control of Complex Network Dynamics and Synchronization by Symbolic Regression

The control of dynamical systems is a relevant and important issue in engineering applications, like turbulence, but also for experimental designs in natural sciences and in medicine, where drugs and technical devices are more and more fine-tuned to enhance the quality of life. Large-scale systems are typically hard to control: due to the many degrees of freedom and related possible instability of modes, linear control is often not effective to control a complex system such that it remains on a well-defined orbit. We use symbolic regression to find *analytical* control laws for the described situations. Here, we use coupled oscillator networks as a general model for a complex network, as e.g., the brain. We investigate in particular the important situation where synchronization is forced/suppressed. The results are analyzed and compared with existing benchmarks. As a result, we conclude that individual control is feasible - an extremely important and useful feature for medicine applications.

Markus W Abel
Universität Potsdam
markus.abel@physik.uni-potsdam.de

Julien Gout
Ambrosys GmbH, Potsdam, Germany
julien.gout@ambrosys.de

Markus Quade
University of Potsdam

Ambrosys GmbH
markus.quade@uni-potsdam.de

Robert K. Niven
he University of New South Wales, Canberra, Australia.
r.niven@adfa.edu.au

Kamran Shafi
UNSW, ADFA, Canberra BC ACT 2610, AUSTRALIA
k.shafi@adfa.edu.au

CP1

The Importance of Assortativity to Improve Dynamical Robustness in Complex Networks

The tolerance to failure of networked systems whose functions are maintained by collective dynamical behavior of the network units has recently been analyzed in the framework called dynamical robustness of complex networks. Understanding this network robustness against failures is useful for preventing large-scale breakdowns and damages in real-world networked systems. However, although the effect of network structure on the dynamical robustness has been examined with various types of network topology, the role of network assortativity is still unclear. Here we study [Sasai T, Morino K, Tanaka G, Almendral JA, Aihara K. LoS ONE 10(4):e0123722 (2015). doi:10.1371/journal.pone.0123722] the dynamical robustness of correlated networks, assortative and disassortative, consisting of diffusively coupled oscillators. To see the effect of the network assortativity, we have fixed the degree distribution of the networks and changed the correlations of the degrees between the connected nodes using two edge-rewiring methods. We show that the network assortativity enhances the dynamical robustness and the network disassortativity can have a positive or negative impact on the dynamical robustness depending on the edge-rewiring method used. Precisely, we find that the disassortative networks with the same assortativity coefficient can have qualitatively different types of topology, leading to the difference in the dynamical robustness.

Juan A. Almendral
Rey Juan Carlos University
Madrid, Spain
juan.almendral@urjc.es

Takeyuki Sasai, Kai Morino
Graduate School of Information Science and Technology
University of Tokyo, Tokyo, Japan
takeyuki_sasai@mist.i.u-tokyo.ac.jp,
morino@mist.i.u-tokyo.ac.jp

Gouhei Tanaka
Aihara Laboratory, Institute of Industrial Science
The University of Tokyo
gouhei@sat.t.u-tokyo.ac.jp

Kazuyuki Aihara
JST/University of Tokyo, Japan
Dept of Mathematical Sciences
aihara@sat.t.u-tokyo.ac.jp

CP1

Convergence of the Spectral Radii for Random Directed Graphs with Community Structure

Prior literature has demonstrated how the spectral radius of the adjacency matrix can impact the dynamics in epidemiological, neuronal and genetic networks. Furthermore, while many results exist regarding the spectral radius for undirected graphs, very few results have been proven for random directed graphs. We first consider the spectral radii distribution for directed Chung-Lu graphs, where the probability two nodes share a directed edge is proportional to the product of the respective expected in and out degrees of the two nodes. We then use a path counting argument to provide novel concentration bounds on the likelihood that the spectral radius of a network of fixed size deviates from the value suggested in the asymptotic theory. Subsequently, we extend our argument to a more general random graph model that allows for community structure, where we partition our adjacency matrix into submatrices. In particular, we prove that if we partition our adjacency matrix with m square blocks on the diagonal, then under modest constraints, the spectral radius of a given realization will asymptotically converge to the spectral radius of an $m^2 \times m^2$ matrix. Ultimately, we anticipate that our novel spectral radius results will not only help us better understand how network structure can influence the dynamics for real world directed networks, but also provide new techniques for estimating the distribution of spectral radii for other random graph models as well.

David Burstein
Swarthmore College
dburste1@swarthmore.edu

CP1

Spatiotemporal Feedback and Network Structure Drive and Encode *C. Elegans* Locomotion

Using a computational model of *Caenorhabditis elegans* connectome dynamics, we show that proprioceptive feedback is necessary for sustained dynamic responses to external input. This is consistent with the lack of biophysical evidence for a central pattern generator, and recent experimental evidence that proprioception drives locomotion. We show that the low-dimensional functional response of the *C. elegans* network of neurons to proprioception-like feedback is optimized by input of specific spatial wavelengths which correspond to the spatial scale of real body shape dynamics. Furthermore, we find that the motor subcircuit of the network is responsible for regulating this response, in agreement with experimental expectations. To explore how the connectomic dynamics produces the observed two-mode, oscillatory limit cycle behavior from a static fixed point, we probe the fixed point's low-dimensional structure using Dynamic Mode Decomposition. This reveals that the nonlinear network dynamics encode six clusters of dynamic modes, with timescales spanning three orders of magnitude. Two of these six dynamic mode clusters correspond to previously-discovered behavioral modes related to locomotion. These dynamic modes and their timescales are encoded by the network's degree distribution and specific connectivity. This suggests that behavioral dynamics are partially encoded within the connectome itself, the connectivity of which facilitates proprioceptive control.

James M. Kunert-Graf
University of Washington
kunert@uw.edu

Joshua L. Proctor
Institute for Disease Modeling
JoshLProctor@gmail.com

Steven Brunton
University of Washington
sbrunton@uw.edu

Nathan Kutz
University of Washington
Dept of Applied Mathematics
kutz@uw.edu

CP1

Nonlinear Control of a Repulsively-Coupled Triad Network with Multiple Attractors

Complex networks are ubiquitous in the natural and man-made world. The ensemble behavior of networks depends on both the nature of the coupling, and the structure of the network. We use the Belousov-Zhabotinsky (BZ) reaction as a model oscillator and control topology by confining the chemistry to micro-fabricated PDMS wells. We report on a theoretical framework that leverages the light sensitivity of the BZ catalyst to switch a ring of three inhibitory coupled wells between two equally strong dynamical attractors. The method, unlike typical control schemes, temporarily alters chemistry to rapidly alter the fixed points of the system and their basins of attraction. By changing the underlying dynamical landscape of the system, the change from one attractor to the other is spontaneous, accomplished without the need for closed-loop active control, underscoring the robustness that can be achieved by judicious network design. The ability to switch readily between stable dynamical attractors is intriguing and provides the fundamental dynamical unit for "gait" switching as well as pointing towards information storage via dynamic states.

Michael M. Norton
Brandeis University
mike.m.norton@gmail.com

Camille Girabawe
Brandeis University
Physics Department
cgira@brandeis.edu

Thomas Litschel
Brandeis University
Department of Biochemistry
tolitsch@brandeis.edu

Seth Fraden
Brandeis University
Department of Physics
fraden@brandeis.edu

CP1

Invariant Subspaces for Pair-Coupled Networks

We characterize invariant subspaces, also called synchrony subspaces, for coupled cell networks with the simplest type of architecture, for several subsets of the admissible vector fields described by Golubitsky, Stewart and others. We consider the case where all the cells have the same internal dynamics, and all the coupling is two-way and identical. Thus, the architecture of the network is a graph. More specifically, we define *uniform pair-coupled systems* of the form

$$\dot{x}_i = f(x_i) + \sum_{j \in N(i)} h(x_i - x_j),$$

where $f : R^k \to R^k$ controls the internal dynamics, $h : R^k \to R^k$ is the coupling function, i labels the vertices of a graph, and $N(i)$ is the set of neighbors of the vertex i. The novel aspect of the present work is the restriction of the admissible vector fields on the coupled cell network to various special classes. The first special case is the set of systems with $h(0) = 0$. In this case, the subspace of fully phase-locked states, with $x_i = x_j$, is a robustly invariant subspace. For some graphs, there are many invariant subspaces that are not a consequence of the symmetry alone. We also consider case where f and h are odd, and the case where f is odd and h is linear. We characterize the invariant subspaces for each class of systems, and give examples of interesting invariant subspaces for several graphs. We apply the results to coupled van der Pol oscillators.

James Swift
Department of Mathematics
Northern Arizona University
jim.swift@nau.edu

CP2

Synchronization of Reaction Diffusion Neural Networks Via Passivity Theory and Its Direct Application to Image Encryption

We study synchronization in dynamical neural networks consisting of N linearly and diffusively coupled identical reaction diffusion neural networks. In order to make the model more general we have considered the effect of time varying delays into the network model. Then, we derive a sufficient condition through constructing the suitable Lyapunov function that ensures the synchronization between the controlled and uncontrolled network model. Further, different types of controllers such as feedback control, sampled data control and passivity control are applied into the addressed system and the advantages of each controller is discussed through numerical approach. Moreover, local stability, global stability, bifurcation analysis, existence of chaos are also revealed through these control techniques. Besides that, the proposed network model is directly applied into the image secure communications that is encryption/decryption process. Based on the solutions obtained from the addressed system are utilized into the process. Statistical analyses such as Histogram, Peak-Signal-Noise-Ratio, Mean-Average-Error, and so on are also done to prove the effectiveness of the proposed encryption algorithm.

Prakash Mani
National Post Doctoral Fellow
prakashgru88@gmail.com

Lakshmanan Shanmugam
Deakin University, Australia
lakshm85@gmail.com

CP2

Dynamic Mode Decomposition of Resting State Eeg Data - a Dynamical Systems Approach to Identifying Epilepsy Characteristics

Electroencephalography (EEG) is commonly used to diagnose epilepsy. However, such diagnoses are at best difficult unless the EEG is performed during or shortly after an epileptic seizure. Recent studies have suggested that the functional connectivity in the resting state (eyes closed but not sleeping) is altered in patients with temporal lobe epilepsy (TLE). We report how such an alteration in the network can be identified by applying the recently developed method called *dynamic mode decomposition* (DMD). Unlike other methods DMD can extract the spatio-temporal dynamics which characterise large scale EEG data. We show how from such an analysis novel numerical measures can be obtained to identify network differences and characteristics for TLE and control subjects.

Karin Mora
University of Paderborn
kmora@math.uni-paderborn.de

Michael Dellnitz
University of Paderborn, Germany
dellnitz@uni-paderborn.de

Solveig Vieluf, Claus Reinsberger
Department of Sports and Health
University of Paderborn, Germany
vieluf@sportmed.uni-paderborn.de,
reinsberger@sportmed.uni-paderborn.de

CP2

Topological Changes in Chaotic Neuron Models

Spike-adding bifurcations are special bifurcations that are common in the slow-fast dynamics of neuron models. Understanding how to generate and control a burst of spikes in neuron cells, and how chaotic behavior can appear in such systems are some of the most fundamental questions in neuroscience. The key questions that we want to address at this presentation are: how this chaotic behavior is organized and how spike-adding bifurcations influence chaotic behavior. We will show how the orbit-flip (OF) codimension-2 bifurcation points, placed in homoclinic bifurcation curves and related with the spike-adding bifurcations, originate countable pencils of period-doubling and saddle-node (of limit cycles) bifurcation lines, but also of symbolic-flip bifurcations. These bifurcations appear interlaced and generate the different symbolic sequences of periodic orbits. These periodic orbits become unstable, constituting the skeleton of the different chaotic attractors and determining their topological structure.

Sergio Serrano, Roberto Barrio
University of Zaragoza, SPAIN
sserrano@unizar.es, rbarrio@unizar.es

Marc Lefranc
PhLAM/Université Lille I,
France
marc.lefranc@univ-lille1.fr

Angeles Martinez
Departamento de Matematica Aplicada and IUMA. CoDy group.
University of Zaragoza, Spain
gelimc@unizar.es

CP2

Effect of Neuromodulation on Connectivity Properites at Hippocampal Synapses

Neurons in a microcircuit connected by chemical synapses can have their connectivity affected by the prior activity of the cells. The number of synapses available for releasing neurotransmitter can be decreased by repetitive activation through depletion of readily releasable neurotransmitter (NT), or increased through facilitation, where the probability of release of NT is increased by prior activation. These competing effects can create a complicated and subtle range of time dependent connectivity. Here we investigate the probabilistic properties of facilitation and depression (FD) for a presynaptic neuron that is receiving a Poisson spike train of input. We use a model of FD that was parameterized with experimental data from a basket cell and pyramidal cell connection (roughly 8-10 synapses were counted), for fixed frequency input spikes. Hence our results will apply to micro circuits in the hippocampus that are responsible for the gamma rhythms associated with learning and memory.

Emily F. Stone
Dept. of Mathematical Sciences
The University of Montana
stone@mso.umt.edu

Elham Bayat-Mokhtari
University of Montana - Missoula
elham.bayatmokhtari@umconnect.umt.edu

CP2

Transient Chaos and Switching Behavior in Two Synaptically Coupled Layers of Morris-Lecar Neurons

Spatiotemporal chaos collapses to either a rest state or a propagating pulse solution in a ring network of diffusively coupled Morris-Lecar neurons. The synaptic coupling of two such ring networks reveals system intrinsic switching of patterns between the layers. E.g., the collapse of spatiotemporal chaos to a pulse in one layer is accompanied in the other layer by the initiation of spatiotemporal chaos from a pulse. Other observed transient behavior includes erratic pulse propagation, pulse distance maximization, or spontaneous systemwide neuron activity.

Renate A. Wackerbauer
University of Alaska Fairbanks
Department of Physics
rawackerbauer@alaska.edu

Harrison Hartley
UAF Physics Department
hthartle@alaska.edu

CP3

Hidden Structures of Information Transport Underlying Spiral Wave Dynamics

A spiral wave is a macroscopic dynamics of excitable media that plays an important role in several distinct systems, including the Belousov-Zhabotinsky reaction, seizures in the brain, and lethal arrhythmia in the heart. Because spiral wave dynamics can exhibit a wide spectrum of behaviors, its precise quantification can be challenging. Here we present a hybrid geometric and information-theoretic approach to quantifying spiral wave dynamics. We demonstrate the effectiveness of our approach by applying it to numerical simulations of a two-dimensional excitable medium with different numbers and spatial patterns of spiral waves. We show that, by defining information flow over the excitable medium, hidden coherent structures emerge that effectively quantify the information transport underlying spiral wave dynamics. Most importantly, we find that some coherent structures become more clearly defined over a longer observation period. These findings provide valid-

ity with our approach to quantitatively characterize spiral wave dynamics by focusing on information transport. Our approach is computationally efficient and is applicable to many excitable media of interest in distinct physical, chemical and biological systems. Our approach could ultimately contribute to an improved therapy of clinical conditions such as seizures and cardiac arrhythmia by identifying potential targets of interventional therapies.

Hiroshi Ashikaga
Johns Hopkins University School of Medicine
hashika1@jhmi.edu

Ryan G. James
University of California, Davis
rgjames@ucdavis.edu

CP3

Spectrum of Singularities in Gravito-Capillary Waves: A Phillips Spectrum Proxy

We report the observation of the spectrum of singularities of gravity surface waves driven by a horizontally moving wave maker interacting with Faraday waves which serve as a Phillips' spectrum proxy. We measure the temporal fluctuations of the surface wave amplitude at a given location and we show that, for a wide range of forcing parameters, they display a power-law spectrum that greatly differs from the one predicted by the WT theory but coincides with Phillips' spectrum for gravity waves. We compute the probability density function of the local surface height increments, which show that they change strongly across time scales. The structure functions of these increments are shown to display power-laws as a function of the time lag, with exponents that are not linear with the order of the structure function, thus showing that the wave field is intermittent. We argue that the origin of this scale-invariant intermittent spectrum is the Faraday wave pattern breakup due to its advection by the propagating gravity waves, which can be related directly to the Phillips' spectrum phenomenology.

Claudio Falcon, Gustavo Castillo
Departamento de Física
Universidad de Chile, Santiago, Chile
cfalcon@ing.uchile.cl, gusanoc@gmail.com

CP3

Slanted Snaking of Localized Faraday Waves

We perform extensive experiments on parametrically excited waves on the surface of a water-surfactant mixture in a vertically vibrated Hele-Shaw cell. The experiments reveal the presence of both spatially extended and spatially localized standing oscillations called Faraday waves. The experiments show that localized Faraday waves are found both inside and outside the hysteresis loop between spatially extended Faraday waves and the flat interface, and that they display a snaking structure that is slanted. We attribute this behavior to the presence of a conserved quantity, the liquid volume, and show that a forced complex Swift–Hohenberg equation coupled to a conserved mode provides an excellent qualitative model for describing the experimental observations, including the observed slanted snaking and the presence of localized waves outside the hysteresis loop. General properties of the model are studied.

Punit R. Gandhi
University of California, Berkeley
gandhi.138@osu.edu

Bastian Last Name, Isidora Araya, Marcel Clerc
Universidad de Chile
bastianpradenasm@gmail.com, isi.melania@gmail.com, marcel@dfi.uchile.cl

Claudio Falcon
Departamento de Física
Universidad de Chile, Santiago, Chile
cfalcon@ing.uchile.cl

Edgar Knobloch
University of California at Berkeley
Dept of Physics
knobloch@berkeley.edu

CP3

Stretching and Speed in Excitable Advection-Reaction-Diffusion Systems

An advection-diffusion-reaction system is said to be excitable if growth occurs only when the local concentration exceeds a critical threshold. Advection (flow) can either start or stop reaction by driving the concentration above or below that threshold. I will present evidence that stretching (the largest eigenvalue of the right Cauchy-Green strain tensor) quantifies that effect, and that an optimal range of stretching maximizes reaction. I will also discuss ongoing work distinguishing the effects of stretching from the effects of speed and precisely measuring the range of optimal stretching.

Douglas H. Kelley
University of Rochester
218 Hopeman Engineering Building Rochester, NY
14627-0132
d.h.kelley@rochester.edu

CP3

Analysis of Pattern Emergence in Turing Systems with Inhomogeneity in Reaction Term

Turing's reaction-diffusion model is widely used as a model for describing self-organized spatial pattern formation and it is well studied in the case of constant coefficients. The spatial dependence yields a wider range of possible patterns but at the same time significantly complicates the analysis. Here, we will consider a small spatial dependency in the coefficient of the linear term of the activator kinetics and analyse the effect of this perturbation on the pattern and the conditions of pattern emergence. At first, we discuss which steady state will be designated as a pattern and which not, then we apply stability analysis and carry out some supportive numerical simulations. Combining both approaches we determine conditions for the emergence of the pattern in such system. Moreover, we obtain a tool for formation of patterns with a spatially varying frequency. These results contribute to complete picture of Turing's model and its possible applicability to real situations.

Michal Kozak
Dept of Mathematics, FNSPE,
Czech Technical University in Prague
atamann13@gmail.com

Vaclav Klika

Czech Technical University in Prague
vaclav.klika@fjfi.cvut.cz

Eamonn Gaffney
Mathematical Institute
University of Oxford
gaffney@maths.ox.ac.uk

CP4

Numerical Simulation of Immiscible and Miscible Component-Based Co2-Oil-Rock Interaction to Enhance Oil Recovery in Heterogeneous Reservoirs

A compositional reservoir simulation was constructed to model the fluid flow through porous media at the CO2 Flooding. The CO2 is injected in heterogeneous reservoirs through vertical injection wells to enhance oil recovery. Oil is produced through horizontal wells at the bottom of the reservoir. That model tracks the CO2-Oil-Rock chemical interactions in reservoir conditions based on their components. Due to the gravity segregation, the gas is accumulating at the top of the reservoir to formulate a gas cap and oil drain down the reservoir towards horizontal production wells. The efficiency of CO2 sweep process depends on the difference between the injection and reservoir pressure. Higher pressure results in miscible flooding and more interaction between CO2 and oil and higher sweep efficiency. In order to show the effectiveness of immiscible and miscible processes to reach promising levels of oil recovery, the compositional model was implemented for a 25 year of prediction period. The incremental recovery factor through immiscible and miscible cases reach to 30% and 42%, respectively. In addition, the production rates during the entire prediction period of the miscible flooding process can also be identified as higher than the immiscible case. However, the miscible continuous CO2 injection leads to a much higher Gas-Oil Ratio than the immiscible case as fast gas flooding cause early gas breakthrough into the oil production wells.

Watheq J. Al-Mudhafar, Dandina N. Rao
Louisiana State University
wmoham4@lsu.edu, dnrao@lsu.edu

CP4

Internal Wave Bolus Detection and Analysis by Lagrangian Clustering

The shoaling of vertical mode internal waves on a continental slope produces boluses, which are trapped regions of fluid that travel up the slope with the wave. Unlike a propagating solitary wave, these boluses transport material with the wave containing oxygen depleted water and induce rapid changes in temperature both of which have potential ramifications for marine biology. We extend a number of two-layer studies by investigating bolus generation and material transport in continuously stratified fluids. Laboratory experiments are conducted in a 4 m long tank and are complemented by 2-dimensional numerical simulations of the Navier-Stokes equations. The boundaries of the bolus are identified using a Lagrangian based coherent structure method relying on trajectory clustering. We investigate how to appropriately implement fuzzy c-means clustering to objectively identify the transported material forming the bolus and measure the properties of the bolus as a function of the pycnocline thickness.

Michael Allshouse
Dept. of Mechanical Engineering
Massachusetts Institute of Technology
m.allshouse@northeastern.edu

CP4

Understanding the Geometry of Transport: Diffusion Maps for Lagrangian Trajectory Data Unravel Coherent Sets.

Dynamical systems often exhibit the emergence of long-lived coherent sets, which are regions in state space that keep their geometric integrity to a high extent and thus play an important role in transport. In this talk, a method for extracting coherent sets from possibly sparse Lagrangian trajectory data is discussed. Our method can be seen as an extension of diffusion maps to trajectory space, and it allows us to construct 'dynamical coordinates' which reveal the intrinsic low-dimensional organization of the data with respect to transport. The only a priori knowledge about the dynamics that we require is a locally valid notion of distance, which renders our method highly suitable for automated data analysis. We show convergence to the analytic transfer operator framework of coherence in the infinite data limit, and illustrate potential applications on several two- and three-dimensional examples as well as real world data.

Ralf Banisch
Freie Universität Berlin
ralf.banisch@fu-berlin.de

Peter Koltai
Free University Berlin
peter.koltai@fu-berlin.de

CP4

Lagrangian Chaos in a Differentially-Heated Three-Dimensional Cavity

Natural convection plays a key role in fluid dynamics owing to its ubiquitous presence in nature and industry. Buoyancy-driven flows are prototypical systems in the study of thermal instabilities and pattern formation. The differentially-heated cavity problem has been widely studied for the investigation of buoyancy-induced oscillatory flow. However, far less attention has been devoted to the three-dimensional Lagrangian transport properties in such flows. This study seeks to address this by investigating Lagrangian transport in the steady flow inside a cubic cavity differentially-heated from the side. The theoretical and numerical analysis expands on previously reported similarities between the current flow and lid-driven flows. The Lagrangian dynamics are controlled by the Péclet number (Pe) and the Prandtl number (Pr). Pe controls the behavior qualitatively in that growing Pe progressively perturbs the integrable state (Pe$\rightarrow$0), thus paving the way to chaotic dynamics. In general, increasing Pe promotes the onset of chaos. Pr plays a quantitative role, it acts as the control parameter for the relative contribution of fluid inertia and convection: "small' and "large' Pr correspond to inertia-dominated and convection-dominated flows, respectively. The transition from inertia-dominated to convection-dominated flow triggers a bifurcation in the Lagrangian flow topology.

Sebastian Contreras Osorio
Eindhoven University of Technology
TU/e
p.s.contreras.osorio@tue.nl

Michel Speetjens
Laboratory for Energy Technology, Dept. Mech. Eng.
Eindhoven University of Technology
m.f.m.speetjens@tue.nl

Herman Clercx
Fluid Dynamics Laboratory, Dept. Applied Physics
Eindhoven University of Technology
h.j.h.clercx@tue.nl

CP4

Angular Dynamics of Non-Spherical Particles Settling in Turbulence

We study the angular dynamics of small spheroidal particles settling in homogeneous isotropic turbulence. Our simulations of the angular dynamics using direct numerical simulation of turbulence show that turbulence induces an orientation bias: disk-like particles tend to settle edge first, and rod-like particles settle tip first. This bias depends sensitively on the turbulent dissipation rate, and on the particle size and shape. We explain the underlying mechanisms using a perturbative analysis of a statistical model. Our results apply to small ice crystals settling in turbulent clods, small enough so that the effect of fluid inertia can be neglected.

Bernhard Mehlig
Gothenburg Univ
Gothenburg, Sweden
Bernhard.Mehlig@physics.gu.se

CP4

Lagrangian Chaos and Transport in Geophysical Fluid Flows

Advances in our understanding of the dynamics of mesoscale eddies and vortex rings of the Agulhas Current Retroflection, and the Gulf Stream in the Middle Atlantic Bight have been based on modons which are nonlinear Rossby solitary wave solutions of quasi-geostrophic equations. This article focuses primarily on geometric singular perturbation (GSP) theory and Melnikov techniques to address the problem of adiabatic chaos and transport for translating and rotating modons to the quasi-geostrophic potential vorticity system which is relevant, e.g., a Lagrangian and Eulerian analysis of a geophysical fluid flow. A very general and central question is what hypotheses on the equations and singular solutions guarantee that the solutions approximate some solutions for the perturbed quasi-geostrophic potential vorticity system. We present a geometric approach to the problem which gives more refined a priori energy type estimates on the position of the invariant manifold and its tangent planes as the manifold passes close to a normally hyperbolic piece of a slow manifold. We apply Melnikov technique to show that the Poincare map associated with modon equations has transverse heteroclinic orbits. We appeal to the Smale-Birkhoff Homoclinic Theorem and assert the existence of an invariant hyperbolic set which contains a countable infinity of unstable periodic orbits, a dense orbit and infinitely many heteroclinic orbits.

Maleafisha Stephen Tladi
University of Limpopo, South Africa
Stephen.Tladi@ul.ac.za

CP5

Dynamical Properties of Viral Defective Interfering Particles

Defective Interfering Particles (DIPs) are non viable viral particles which occur rarely in Nature and have the capability of displacing wild type viruses, slowing down or even preventing infection. Their occurrence has been shown in several RNA viral species, including Polio, Ebola and HIV. The dynamical properties of these particles, and their co-evolutionary dynamic with co-infecting viral species, have not been widely investigated. We will present a multiscale model which accounts for the competition between DIPs and wild type viruses. Deterministic and stochastic simulations of DIPs replication models and analysis of experimentally viable parameter phase space allows for effective design of DIPs as therapeutic. A set of experimental results on Poliovirus will be presented to support the model.

Simone Bianco
IBM Research
sbianco@us.ibm.com

Igor Rouzine
University of California San Francisco
igor.rouzine@ucsf.edu

CP5

Impact of Heart Tissue Anisotropy and Ischemic Heterogeneities on Unpinning and Termination of Pinned Spirals: Insights from Simulations.

Reentries are strictly related to the complex structure of cardiac tissue, characterized by multi-sized heterogeneities. Spiral waves pinned to an heterogeneity can either undergo a process of spontaneous termination or be unpinned (and terminated) using electric far field pulses recruiting the heterogeneity as a virtual electrode. We implement a bidomain formulation of the phase I of the Luo and Rudy model in 2D under ischemia. We investigate how size of ischemic heterogeneities and tissue anisotropic properties may affect the evolution of reentrant dynamics in the presence and in the absence of far field pacing (FFP). In absence of FFP, the main findings show that: a) for the stability of the waves, changes of conductivity in the intracellular space are more critical than alterations in the extracellular space; b) the maintenance or the self-termination of pinned spirals is strongly dependent not only on the size of the heterogeneities but also on the degree of intracellular anisotropy. Unpinning and termination of pinned spirals under FFP are better understood in isotropic media than in anisotropic substrates. Therefore, to study the impact of anisotropy, we compare the success of sequences of far field pulses in the isotropic and in the anisotropic cases. Our results clearly indicate that the range of pacing parameters resulting in successful termination of pinned spiral waves is larger in anisotropic than in isotropic tissues.

Edda Boccia
Max Planck Institute for Dynamics and Self-Organization
edda.boccia@ds.mpg.de

Stefan Luther, Ulrich Parlitz
Max Planck Institute for Dynamics and Self-Organization
Research Group Biomedical Physics

stefan.luther@ds.mpg.de, ulrich.parlitz@ds.mpg.de

CP5

Transovarial Transmission in Vector-Borne Relapsing Diseases

In this talk we consider a relapsing disease in which there are two modes of transferring the disease throughout the host and vector populations: interaction between vectors and hosts, and the transmission of the disease to the progeny of a vector. We examine how each of these mechanisms drives the persistence of the disease and give conditions for determining which mechanism is the dominant driver of disease spread. We then discuss how this information informs control strategies for the disease.

Cody Palmer, Erin Landguth, Tammi Johnson
University of Montana
cody.palmer@louisiana.edu, erin.landguth@gmail.com, uzj6@cdc.giv

CP5

Global Stability of Zika Virus Mathematical Model with Recurrence Based on Treatment

In this paper, a mathematical model for dynamic of zika virus with recurrence based on treatment is proposed and analyzed for stability of infected states. The virus free and endemic equilibrium are locally stable if they are less than unity and unstable if greater than unity. A threshold parameter is obtained to check the spread of the virus qualitatively and quantitatively. It has been shown that the timely treatment to zika virus lead to the effective control of zika virus. Sensitivity analysis is also carried out to see the effects of zika virus on environment.

Ram Singh
Baba Ghulam Shah Badshah University
singh_ram2008@hotmail.com

CP5

Geometric Analysis of Fast-Slow Models for Stochastic Gene Expression

Stochastic models for gene expression frequently exhibit dynamics on several different scales. One such time-scale separation is caused by significant differences in the lifetimes of mRNA and protein; the ratio of the two degradation rates appears as a small parameter in the associated Chemical Master Equation, allowing for the application of perturbation techniques. We present a framework for the analysis of a family of fast-slow models for gene expression, based on geometric singular perturbation theory. We demonstrate the approach by giving a complete characterisation of a standard two-stage model which assumes transcription, translation, and degradation to be ?rst-order reactions. We present a systematic expansion procedure for the probability-generating function that can be taken to any order in the perturbation parameter, allowing for an approximation of the corresponding propagator probabilities to that order. Focussing on biologically relevant parameter regimes that induce translational bursting, as well as those in which mRNA is frequently transcribed, we find that the first-order correction can significantly improve the steady-state probability distribution. Similarly, in the time-dependent scenario, inclusion of first-order fast asymptotics yields an approximation for the propagator probabilities that is superior to the slow dynamics alone. We discuss the application of our geometric framework to models for regulated gene expression that involve additional stages.

Frits Veerman, Nikola Popovic
University of Edinburgh
fveerman@ed.ac.uk, nikola.popovic@ed.ac.uk

Carsten Marr
Institute for Computational Biology
Helmholtz Centre Munich
carsten.marr@helmholtz-muenchen.de

CP5

Dynamic Responses of a Steroidogenic Regulatory Network to Physiological Perturbations

The stress response is mediated by glucocorticoid hormones (CORT) secreted by the adrenal glands upon stimulation by adrenocorticotropic hormone (ACTH) from the pituitary. These hormones exhibit a complex pattern of highly correlated ultradian oscillations that becomes altered during inflammation. In particular, the role of intra-adrenal control mechanisms on the dynamic dissociation of these hormones is poorly understood. We explore the origins of this dissociated dynamics through a mathematical model of the intra-adrenal regulatory network controlling the synthesis of CORT, accounting for both genomic and non-genomic processes occurring at different time scales within the network. We test the model through computer simulations of ACTH perturbations, and successfully predict responses to acute stressors, as judged from experiments in rats injected with single pulses of ACTH and a bacterial toxin (LPS) that triggers an inflammatory response. Our results suggest that a negative feedback loop, genomic and non-genomic processes occurring at different time scales, and post-transcriptional and post-translational regulation are essential control mechanisms for the network to mount a fast, transient, and controlled CORT response to ACTH. We also show that cross-talk between the immune pathway and the steroidogenic regulatory network may underlie the ACTH/CORT dissociated dynamics, and suggest the presence of novel regulatory mechanisms that can be tested experimentally.

Eder Zavala
University of Exeter
e.zavala@exeter.ac.uk

Francesca Spiga
University of Bristol
f.spiga@bristol.ac.uk

Jamie Walker
University of Exeter
jamie.walker@exeter.ac.uk

Zidong Zhao
University of Bristol
zidong.zhao@bristol.ac.uk

Stafford Lightman
University of Bristol, United Kingdom
Stafford.Lightman@bristol.ac.uk

John Terry
University of Exeter.

j.terry@exeter.ac.uk

CP6

When Chaos Meets Hyperchaos: a Computer-Assisted Proof on the 4D Rossler Model

It has recently been reported that it is quite difficult to distinguish between chaos and hyperchaos in numerical simulations which are frequently "noisy'. In this presentation we show that, for the classical 4D Rossler model, the coexistence of two invariant sets with different nature (a global hyperchaotic invariant set and a chaotic attractor) and the homoclinic and heteroclinic connections between their unstable periodic orbits give rise to long hyperchaotic transient behavior, and therefore it provides a mechanism for noisy simulations. The Computer-assisted proof of this coexistence of chaotic and hyperchaotic behaviors combines topological and smooth methods with rigorous numerical computations. The existence of (hyper)chaotic sets is proved by the method of covering relations and cone conditions.

Roberto Barrio
University of Zaragoza, SPAIN
rbarrio@unizar.es

Angeles Martinez
Departamento de Matematica Aplicada and IUMA. CoDy group.
University of Zaragoza, Spain
gelimc@unizar.es

Sergio Serrano
University of Zaragoza, SPAIN
sserrano@unizar.es

Daniel Wilczak
Jagiellonian University, Krakow, POLAND
wilczak@ii.uj.edu.pl

CP6

Bounding Time Averages Rigorously Using Semidefinite Programming

I will describe computer-assisted methods for proving bounds on infinite-time averages in differential dynamical systems. The methods rely on the construction of nonnegative polynomials with certain properties, similarly to the way nonlinear stability can be proven by the construction of Lyapunov functions. Nonnegativity is enforced by requiring the polynomials to be sums of squares, a condition which is then formulated as a semidefinite program (SDP) that can be solved computationally. Although such computations are subject to numerical error, rigorous results can be obtained in one of two ways: using interval arithmetic to control the error of an approximate SDP solution, or finding exact analytical solutions to relatively small SDPs. I will illustrate these methods using the Lorenz equations, for which they produce novel bounds on time averages of a number of different quantities. Some of these bounds, such as the upper bound on the average of z^3, are perfectly sharp and depend analytically on the control parameter r. Many other bounds are within 1% of being sharp, which would be nearly impossible without computer assistance.

David Goluskin
Deparment of Applied Mathematics
Columbia University
goluskin@umich.edu

CP6

The Search for the Smallest Chimera

We demonstrate that chimera behavior can be observed in small networks consisting of three identical oscillators, with mutual all-to-all coupling. Three different types of chimeras, characterized by the coexistence of two coherent oscillators and one incoherent oscillator, (i.e. rotating with another frequency) have been identified, where the oscillators show periodic (two types) and chaotic (one type) behaviors. Typical bifurcations at the transitions from full synchronization to chimera states and between different types of chimeras have been identified. Parameter regions of synchronization for the chimera states are obtained in the form of Arnold tongues, issued from a singular parameter point. Our analusis suggests that chimera states can observed in small networks, relevant to various real-world systems.

Tomasz Kapitaniak
Technical University of Lodz
Dept of Dynamic
tomaszka@p.lodz.pl

CP6

Chimeras and Chaotic Mean Field Dynamics in Two Populations of Phase Oscillators with Heterogeneous Phase-Lag

The simplest network of coupled phase-oscillators exhibiting chimera states is given by two populations with disparate intra- and inter-population coupling strengths. We explore the effects of heterogeneous coupling phase-lags between the two populations. Such heterogeneity arises naturally in various settings in nature and technology. Breaking the phase-lag symmetry results in a variety of states with uniform and non-uniform synchronization, including in-phase and anti-phase synchrony, full incoherence, chimeras with 0 or π phase separation between populations, and states where both populations remain desynchronized. These desynchronized states exhibit stable, oscillatory, and even chaotic dynamics. We identify the bifurcations through which chimera and desynchronized states emerge and analyze how chaotic mean field dynamics arises. While these chaotic dynamics are attractors in the Ott-Antonsen equations, the finite size system displays only transient chaos – thus we address a question raised by Ott and Antonsen. We discuss how associated decay times scale with system size and are affected by oscillator heterogeneity. These findings elucidate previous experimental results in a mechanical oscillator network of and provide insight into the breakdown of synchrony in biological systems.

Erik A. Martens
University of Copenhagen
Max Planck Institute for Dynamics & Self-Organization
erik.martens@ds.mpg.de

Christian Bick
University of Exeter, UK
bick@maths.ox.ac.uk

Mark J. Panaggio
Engineering Science and Applied Mathematics
Northwestern University

markpanaggio2014@u.northwestern.edu

CP6

Pseudorandom Number Generation Using Chaotic True Orbits of the Bernoulli Map on Algebraic Integers

We introduce two methods for generating pseudorandom binary sequences using true orbits of the Bernoulli map $x \mapsto 2x \bmod 1$. The characteristic of these methods is that they exactly compute chaotic orbits of the Bernoulli map on algebraic integers of degree two and three. In addition, we develop ways to properly select initial points (seeds), which can distribute initial points almost uniformly (equidistantly) in the unit interval and which can avoid mergers of the orbits starting from them. We also demonstrate through statistical testing that the generated sequences have good randomness properties. (See [A. Saito and A. Yamaguchi, Chaos **26**, 063122 (2016)] for details of the pseudorandom number generation using algebraic integers of degree two.)

Asaki Saito
Future University - Hakodate
saito@fun.ac.jp

Akihiro Yamaguchi
Fukuoka Institute of Technology
aki@fit.ac.jp

CP6

Homotopy Method for Characterizing Topological Chaos in Three Dimensions

In a wide variety of physical systems, the dynamics of topologically robust structures underlie a powerful class of tools for characterizing complexity. While many such topological techniques have been applied to great effect in 1D and 2D dynamics, extending their reach to 3D systems has proven to be quite difficult. We successfully modify the homotopic lobe dynamics (HLD) technique to work for 3D volume preserving maps. Specifically, we use intersecting two-dimensional stable and unstable invariant manifolds to construct a symbolic representation of the topological dynamics. This symbolic representation can be used to compute measures of complexity, such as the topological entropy, and discover distinct regions of the system which have qualitatively different behavior. We apply the 3D HLD technique to an explicit numerical example in fluid dynamics: a time-periodic perturbation of Hill's spherical vortex, modified to break both rotational symmetry and integrability. Importantly, the 3D HLD topological technique is able to detect a distinction between the topologically forced 2D stretching rate of material surfaces and the 1D stretching rate of material curves, illustrating the truly 3D nature of our approach. Additionally, the symbolic dynamics point towards an intriguing duality between the regions participating in 2D and 1D stretching.

Spencer A. Smith
Mount Holyoke College
smiths@mtholyoke.edu

Joshua Arenson
University of California Merced
jarenson@ucmerced.edu

Kevin A. Mitchell
University of California, Merced
Physics
kmitchell@ucmerced.edu

CP7

Phase Space Transport in Hydrogen in Crossed Fields: Role of the Local Surface of Section

Ionization of hydrogen in crossed electric and magnetic fields has been of scientific interest for many years. Not only is this a beautiful example of a chaotic system, but it is also widely considered a stepping stone to understanding the escape in the classic gravitational three body problem The electrons classical motion resembles the motion of the Moon in the Sun-Earth-Moon three body system. One of the major challenges in studying chaotic ionization of hydrogen in crossed electric and magnetic fields is the ability to define a Poincare surface of section that captures all the allowed electron trajectories, but at the same time does not suffer from tangencies. We will present a prescription for defining a Poincare return map that defines a local surface of section which governs the ionization process.

Korana Burke
UC Davis
kburke@ucdavis.edu

Kevin A. Mitchell
University of California, Merced
Physics
kmitchell@ucmerced.edu

CP7

Internal Transport Barriers in Plasmas with Reversed Plasma Flow

We investigate the influence of the radial electric field profile on internal particle transport barriers in plasma discharges with reversed plasma flow. In this investigation we apply a bidimensional symplectic drift wave map that describe the plasma particle transport and allows the integration of the particle drift in the presence of a given electrostatic turbulence spectrum. With this procedure we show that the reversed flow gives rise to shearless invariant lines, acting as transport barriers inside the plasma. Moreover, by varying the radial electric field profile, we observe the formation and destruction of these internal transport barriers. Applicability of our results are discussed for the Texas Helimak, a toroidal plasma device in which the radial electric field can be changed by application of bias potential.

Ibere L. Caldas
Institute of Physics
University of Sao Paulo
ibere@if.usp.br

Rafael Ferro
Institute of Physics, University of Sao Paulo
rafael.ferro@outlook.com

CP7

Whole-Building Fault Detection: A Scalable Approach Using Spectral Methods

Rules-based fault detection (i.e. expert systems) have become ubiquitous as an approach to designing a decision-making support system. In particular, building management systems (BMS) make extensive use of rules-based techniques to monitor telemetry data generated that is generated by the large array of devices that are present in commercial buildings. In this talk, an extension to rules-based fault detection is demonstrated utilizing properties of the Koopman operator. The Koopman operator is an infinite-dimensional, linear operator that captures nonlinear, finite dimensional dynamics. The definition of the Koopman operator enables algorithms that can evaluate the magnitude and coincidence of time-series data. Using properties of this operator, diagnostic rule signals from building management system (BMS) trend data can be decomposed into components that allow the capture of device behavior at varying time-scales and to a granular level. As it relates to the implementation of fault detection (FDD), this approach creates additional spatial and temporal characterizations of rule signals providing additional data structure and increasing effectiveness with which classification techniques can be applied to the analysis process. The approach permits a knowledge base to be applied in a similar manner to that of a rules-based approach, but the introduced extensions also facilitate the definition of new kinds of diagnostics and overall provide increased analysis potential.

Michael Georgescu
University of California, Santa Barbara
mvgeorge@engineering.ucsb.edu

CP7

Numerical Study of Mixed Convection Effects in a Ventilated Room with Different Locations of Thermosolutal Block

A mixed convection analysis is performed over a ventilated domain to find the thermal and solutal effects over a thermosoluted block by supplying mechanically driven cold air at the inlet. The block is maintained with higher temperature and concentration than that of inlet fluid and the walls are considered as impermeable and adiabatic to heat and solute. To study the density influence over the fluid, the cold fluid is performed at the lower left vertical wall and flushes out through the upper section of the opposite wall. The mixed air distribution and thermosolutal effective rates due to the adiabatic source is analysed by changing the block position to obtain the appropriate position for maximum cooling/heating. The efficient cooling and maximum variation of average temperature is obtained for higher Richardson number and Reynolds number for a fixed Prandtl number (Pr = 0.71) with buoyancy ratio (Br=1.0).

Neha Gupta
Research Scholar
Department of Mathematics, IIT Roorkee
nehagupta3192@gmail.com

Ameeya Nayak
Indian Institute Of Technology Roorkee
ameeyakumar@gmail.com

CP7

Newton-Krylov Continuation for Annular Electroconvection

We investigate the flow transitions in sheared annular electroconvection using matrix-free numerical bifurcation methods. In particular, we study a model that simulates the flow of a liquid crystal film in the Smectic A phase suspended between two annular electrodes, and subjected to an electric potential difference and a radial shear. Due to the Smectic A nature of the liquid crystal, the fluid can be considered two-dimensional and is modelled using the 2-D incompressible Navier-Stokes equations coupled with an equation for charge continuity. A Newton-Krylov method is implemented to identify the transitions of the flow that result due to changes in the model parameters. The primary transition from axisymmetric flow to rotating waves and the secondary transition from rotating waves to amplitude vacillation (i.e. amplitude-modulated waves) are investigated. The rotating waves are relative equilibria of the system, and we discuss the effectiveness of using this characteristic to simplify the computations.

Greg Lewis, Jamil Jabbour
UOIT
greg.lewis@uoit.ca, jamilantoinejabbour@gmail.com

Mary Pugh
University of Toronto
Department of Mathematics
mpugh@math.toronto.edu

Stephen Morris
University of Toronto, Canada
smorris@physics.utoronto.ca

CP7

Rotating Stall in Turbomachinery Compressors: a Dynamical Systems Approach

Turbomachinery compressors experience rotating stall as the operating conditions for maximum efficiency are approached. Rotating stall consists of a spatially localized pulse of flow blockage that covers a few blade passages and rotates at a fraction of the rotating speed of the compressor. The prediction and control of stall onset is of great interest for the Turbomachinery industry since it has a strong negative impact in the performance of the compressor, and it also generates large unsteady loads that increase the vibration level of the compressor blades, and can ultimately lead to blade failure. Rotating stall can be regarded as a solitary wave that propagates from blade to blade around of the compressor rotor. In this presentation we will give and introductory overview of the stall phenomena in turbomachinery compressors, which is a very interesting example of a localized propagating state that appears in a realistic industrial situation. We will present some numerical simulations of rotating stall in a simplified 2D linear cascade, and we will also discuss the possibility and advantages of using the tools from Dynamical Systems to analyze stall onset and propagation.

Carlos Martel
Universidad Politecnica de Madrid
carlos.martel@upm.es

CP8

Stabilized Coexistence Among Mutual Cheaters in Cyclic Public Goods Games with Optimized Taxation

We study the problem of stabilized coexistence in a three-species public goods game in which each species simultaneously contributes to its own public good while freeloading off another species' public good. We assume population growth is governed by absolute success as a function of the profit from a species' own public good as well as the return from free-loading off another public good. We show that proportional population growth is governed by a replicator dynamic with at most one interior unstable fixed point; i.e. that the population becomes dominated by a single species. We then show that applying an externally imposed "tax" on success can stabilize the interior fixed point, allowing for the symbiotic coexistence of all species. We show that the interior fixed point is the point of globally minimal total population growth (in number of species) in both the taxed and un-taxed cases and discuss a criterion under which the populations will collapse. We also show that these dynamics do not admit limit cycles through a diffeomorphic mapping to traditional rock-paper-scissors. Finally, we formulate an optimal taxation problem, and show that it admits a quasi-linearization that results in novel necessary conditions for the optimal control. In particular, the optimal control problem governing the tax rate must solve a certain second order ordinary differential equation.

Christopher H. Griffin
Applied Research Laboratory
Penn State University
griffinch@ieee.org

Andrew Belmonte
Department of Mathematics, Pennsylvania State University
andrew.belmonte@gmail.com

CP8

Pedestrian Dynamics from Social Force Models

Numerical simulation of pedestrians moving as mass points under the action of social forces and reacting to forces from obstacles provides a way to study crowd phenomenae. Many such social force models with inflexible parameters suffer from limited validity when they are applied to various scenarios. We give examples of this, and demonstrate pathological cases of unrealistic stationary points arising in models with potential forces. To overcome this problem we propose, and mathematically formalize, a novel hybrid modeling approach including dissipation via a friction term, where pedestrian behavior is situation-dependent, i.e., switches between equations of motion according to the relative location to an obstacle. A number of scenarios are studied to illustrate the advantages of such a hybrid model approach.

Poul G. Hjorth
Technical Univ of Denmark
Department of Applied Mathematics and Computer Science
pghj@dtu.dk

CP8

Dynamics of Arrays of Coupled Cilia and Flagella-like Structures Driven by Axonemal Beating

Cellular beating protrusions such as cilia and flagella are comprised of bundles of filaments internally connected by rod-like tubular elements called axonemes. Cilia are used by cell-like structures for swimming and generally locomote in fluids and analogous physical media. Recent work focused on the dynamics of cilia and cilia arrays has revealed important features such as array alignments, two-phase asymmetric beating of individual filaments, and the emergence of metachronal coordination with constant phase difference between contiguous cilia. The main underlying mechanisms for these individual and cooperative behaviors have been identified as hydrodynamic coupling and internal electrochemical motors, with periodic motions arising from a Hopf bifurcation dynamic instability predicted by a model of a double elastic filament with axonemal connections. The rich dynamics of cilia-like structures against the relatively simple internally driven mechanism, which is based on differential axial displacements of the filaments at the common base, make them suitable for robotic applications that aim at miniaturization and bio-affinity. By considering mechanical coupling through the base rather than through environment hydrodynamics, we analyze the collective dynamics of arrays of double elastic filaments with axonemal connections. Synchronised patterns solution such as metachronal waves hint at the possibility of using the model for bio-inspired terrestrial locomotion.

Davide Spinello
University of Ottawa
davide.spinello@uottawa.ca

CP8

Fish Schooling

Fish schooling, one of animal swarming, is a commonly observed phenomenon that is coherently performed by integration of interactions among constituent fish. This remarkable phenomenon has already attracted interests of researchers from diverse fields including biology, physics, mathematics, computer engineering. In this talk, we will present

(1) our fish schooling model. The model is performed by stochastic differential equations.

(2) quantitative investigations for the model.

(3) pattern formation for fish schooling. Four obstacle avoiding patterns of school have been observed, i.e., Rebound, Pullback, Pass and Reunion, and Separation which are performed just by tuning modeling parameters.

(4) a scientific definition of the school cohesiveness.

Ton V. Ta, Linh Nguyen
Kyushu University
tavietton@agr.kyushu-u.ac.jp, nth.linh@ist.osaka-u.ac.jp

Atsushi Yagi
Osaka University
atsushi-yagi@ist.osaka-u.ac.jp

CP8

Mapping of Large-Scale Biological Dynamical Networks

The unprecedented accumulation of high-throughput temporal biological data (e.g. gene expression, brain imaging data) provides an essential opportunity for researchers to study the dynamics of biological systems. At the same time, it raises new questions and grand challenges for applied mathematicians in view of the key characteristics of these data that include high-dimensionality, multi-scale, and heterogeneity. In response, we recently developed a computational framework to model the temporal biological data by identifying and mapping of large-scale dynamical networks in a data-driven approach. The topological and statistical tools that we developed to encode and map the dynamical networks work very efficiently. We applied this method in the analysis of brain development gene networks and provided novel insights into the field of mathematical

biology.

Lin Wan
Chinese Academy of Sciences
lwan@amss.ac.cn

CP8

How NF-κB Oscillations Drive Stochastic Gene Expression

Understanding how cells process information by translating external stimuli into an adequate transcriptional response is a fundamental question in molecular biology. Transcription factors play a key role in this process and for this reason they are typically tightly regulated by complex genetic circuits. This is the case of the transcription factor NF-κB, whose deregulation can lead to chronic inflammation and cancer: its activity is regulated by negative feedbacks that lead to damped oscillations upon external stimuli. Using population-level observations, we have shown that such oscillations produce different dynamics of gene expression for different genes. However, we are far from understanding how NF-κB modulates stochastic gene expression in single cells. We have used a simple mathematical model of the NF-κB regulatory system with just one negative feedback loop- to show that the stochastic patterns of gene activation-inactivation are determined by a precise combination of the timescales of the model. We will present here our first insights on how such patterns are affected when additional layers of complexity are added to the model. Finally, we will also present our first experimental data on how NF-κB regulates transcription in single cells, which suggest that unexpected mechanisms of regulation of gene activity different to those included in the mathematical models- might be in place.

Samuel Zambrano
San Raffaele University
zambrano.samuel@hsr.it

Nacho Molina
Institut de Génétique et Biologie Moléculaire Cellulaire
Illkirch, France
nacho.molina@igbmc.fr

Davide Mazza, Alessia Loffreda
Experimental Imaging Center Ospedale San Raffaele
Milan, Italy
mazza.davide@hsr.it, loffreda.alessia@hsr.it

Marco Bianchi
San Raffaele University
Milan, Italy
bianchi.marco@hsr.it

Alessandra Agresti
San Raffaele Research Institute, Milan (Italy)
agresti.alessandra@hsr.it

CP9

Unstable Manifolds of Relative Equilibria and Relative Periodic Orbits

Many nonlinear partial differential equations of practical interest, such as Navier-Stokes equations, are equivariant under continuous symmetries. These systems tend to have high-dimensional time-invariant sets such as relative equilibria (traveling and rotating waves) and relative periodic orbits. In this talk, I will present numerical methods for computing unstable manifolds of these orbits and show examples of such calculations on Kuramoto-Sivashinsky equation in one space dimension, and three-dimensional Navier-Stokes equations.

Nazmi Burak Budanur
School of Physics and Center for Nonlinear Science
Georgia Institute of Technology, Atlanta GA 30332
burak.budanur@ist.ac.at

CP9

Exploring Relations Between Smooth and Piecewise Smooth Models

Piecewise smooth and slow-fast systems are frequently used as alternative mathematical representations of the same phenomenon. From an applied scientists perspective, having a choice between two languages can be useful, for instance to pick the most appropriate formalism for a given numerical analysis tool, as long as the differences in the results that can be expected are well understood. Unfortunately, the differences in the behaviour of a smooth and piecewise smooth system that were built to be close are rarely well understood. This problem has been addressed, with some success, in the literature. What we propose here is a small extension of this branch of research, mostly built on classical results available in Filippov's book. Our main results can be roughly stated as follows: Statement 1. The dynamics of a piecewise smooth system is a superset of the dynamics of the smooth system it represents (i.e., of its smoothing). Statement 2. The bifurcation diagram of a piecewise smooth system contains all transitions in the bifurcation diagram of its smoothing, but some of these transitions can take place simultaneously.

Alessandro Colombo
Politecnico di Milano
alessandro.colombo@polimi.it

CP9

Internally Delayed Oscillator in Coupling

While delay effects in coupled dynamical systems are frequently caused by travel time within the network, there may also be delay within the individual units, due to information processing and reaction time. These internal delay effects may cause oscillations in individual units where oscillatory behavior would not otherwise occur. In the context of the coupled system, this may also bring additional frequencies and resonances into consideration.
As an example, the single first-order autonomous delay differential equation $x'(t) = -x(t-T) - (x(t))^3$ exhibits a stable limit cycle for large enough delay. This delay limit cycle oscillator has been shown to behave similarly to ODE oscillator models in some situations. Using perturbation methods and bifurcation theory, I will explore the behavior of this delay oscillator model when it is coupled to an oscillator defined by an ODE.

Lauren Lazarus
Harvey Mudd College
llazarus@g.hmc.edu

CP9

Dynamics of Some Nonanalytic Singular Perturbations of $z^2 + c$

We study the dynamics of several families of maps of the real plane which are perturbations of the well-studied complex quadratic map $z^2 + c$. All maps are subfamilies of the following family: $z^2 + c + \frac{\alpha}{z^{d_1}} + \frac{\beta}{\bar{z}^{d_2}}$. Comparisons are made in both phase space and parameter space to the unperturbed family $z^2 + c$, as well as to the analytic analogues (with $\beta = 0$) studied over the last two decades by R. L. Devaney [Devaney, "Singular Perturbations of Complex Polynomials', Bull. Amer. Math. Soc. 50 (2013), 391-429], coauthors, and others over the last two decades.

Bruce B. Peckham
Dept. of Mathematics and Statistics
University of Minnesota Duluth
bpeckham@d.umn.edu

CP9

Dynamics of Iterated Holomorphic Function Systems

In this talk I focus on the dynamics of backward iterated function systems corresponding to the sequences of holomorphic functions from the unit disk into a subdomain of it. Lorentzen and Gill showed that if the subdomain is relatively compact in the unit disk, then every iterated function system has a unique limit function which is constant. In other words, they showed that relative non-compactness of X is necessary to have a boundary point as a limit function. Keen and Lakic used the notion of hyperbolic Bloch domain, first introduced by Beardon et al., and showed that if X is not Bloch in D, every boundary point of X is a limit function of some iterated function system. In this talk I generalize this result and show that relative non-compactness of X in D is a sufficient condition to have a boundary point as a limit function. This result has important applications in studying the degeneracy of the phenomena which are modeled by the above iterated function systems.

Kourosh Tavakoli
Oklahoma City University
ktavakoli@okcu.edu

CP9

Generalizations of Conley Index and Relevant Applications.

Conley index, as a homotopy index, is a useful tool to study the unstability of invariant sets of autonomous dynamical systems. In view of its continuation, Conley index has been applied to solve some bifurcation problems of invariant sets, such as dynamic or global bifurcations.The generalization of Conley index can be considered in three ways. One is extending the phase space to more common ones. Rybakowski has built up the theory on non-local compact spaces, and we rebuilt this theory in a more simple way. Another is generalizing the homotopy index to shape index, since shape is a generalization of homotopy type. We have defined a kind of compact generated shape index of compact invariant sets in non-local compact spaces. The third one is to consider more complicate nonautonomous dynamical systems. However, this generalization is far from a trivial one and I am focusing on this issue now. In this lecture, I will introduce the work I have done and am about to do in this topic.

Jintao Wang
Huazhong University of Science and Technology
Wuhan, China
wangjt425@tju.edu.cn

CP10

Solution Surfaces of PDE's As Families of Orbit Segments

We consider first order quasilinear partial differential equations of the form

$$P(x, y, z)z_x + Q(x, y, z)z_y = R(x, y, z),$$

with $(x, y, z) \in \mathbf{R}^3$. These PDEs arise in many applications ranging from traffic flow and gas dynamics to high energy physics and birth/death processes. A solution

$$S = \{(x, y, z) \in \mathbf{R}^3 |\ z = f(x, y)\}$$

of this PDE corresponds to an integral surface of the associated vector field

$$X : \begin{cases} \dot{x} &= P(x, y, z), \\ \dot{y} &= Q(x, y, z), \\ \dot{z} &= R(x, y, z), \end{cases}$$

i.e., the vector field X is tangent to S in every point. Given suitable initial data, the method of characteristics allows one to obtain a functional expression for S. However, in a general context, this task may demand hard algebraic work from X; and even if one manages to get a formula by this method, its practical usefulness is not assured. In this talk, we take a geometric approach for the initial value problem rather than a formulaic one: We compute the solution surfaces S as families of orbit segments of the vector field X obtained as solutions of a two-point boundary value problem solved by continuation methods. This novel approach allows us to get useful insight into the geometrical properties of the surface S and, ultimately, of the solution $z = f(x, y)$. We illustrate this method with an example that arises in the study of one-dimensional neutron transport theory.

Pablo Aguirre
Universidad Técnica Federico Santa María
Departamento de Matemática
pablo.aguirre@usm.cl

CP10

Snaking and Localized Patterns with Twisted Invariant Manifolds

We analyze the bifurcation diagrams associated with spatially localized stationary patterns, often known as localized rolls. In a wide variety of contexts, such diagrams exhibit a phenomenon known as snaking, due to their intertwined S-shaped bifurcation curves. When the localized patterns satisfy a reversible, conservative ODE in R^4, snaking has previously been rigorously analyzed by connecting the existence of the localized rolls with the bifurcation structure of fronts that connect the rolls to the trivial state. In previous work, important assumptions were made that ensured the rolls had real Floquet exponents, and additionally that their stable and unstable manifolds were not twisted. In this work, we show that such twisting produces a topological obstruction to snaking behavior, while isolas and ladders can still appear in the bifurcation diagram.

Paul Carter
Department of Mathematics
University of Arizona

pacarter@math.arizona.edu

Tarik Aougab
Department of Mathematics
Brown University
tarik_aougab@brown.edu

Margaret Beck
Boston University
mabeck@math.bu.edu

Surabhi Desai
Mathematical Institute
University of St. Andrews
sd207@st-andrews.ac.uk

Bjorn Sandstede
Division of Applied Mathematics
Brown University
bjorn_sandstede@brown.edu

Melissa Stadt
Department of Mathematics
University of Washington
melissa.stadt@gmail.com

Aric Wheeler
Department of Mathematics
UNC Chapel Hill
arica@live.unc.edu

CP10

Fractional Integrated Semi Groups and Non Local Cauchy Problem for Abstract Nonlinear Fractional Differential Equations

Some classes of fractional abstract differential equations with α-integrated semi groups are studied in Banach space. The existence of a unique solution of the nonlocal Cauchy problem is studied.

Mahmoud M. El-Borai
Professor of Mathematics Faculty of Science Alexandria Unive
Alexandria University Egypt
m_m_elborai@yahoo.com

CP10

Revisiting Delay-Embedding by Using Hilbert-Schmidt Integral Operator Theory for Dynamical Reconstruction

Delay embedding is well-known for non-linear time-series analysis, and it is used in several research fields. Takens theorem ensures validity of the delay embedding analysis: embedded data preserves topological properties, which the original dynamics possesses, if one embeds into some phase space with sufficiently high dimension. This means that, for example, an attractor can be reconstructed by the delay coordinate system topologically. However, configuration of embedded data may easily vary with the delay width and the delay dimension, namely, "the way of embedding". In a practical sense, this sensitivity may cause degradation of reliability of the method, therefore it is natural to require robustness of the result obtained by the embedding method in certain sense. In this study, we investigate the mathematical structure of the framework of delay-embedding analysis to provide Ansatz to choose the appropriate way of embedding, in order to utilise for time-series prediction. In short, mathematical theories of the Hilbert-Schmidt integral operator and the corresponding Sturm-Liouville eigenvalue problem underlie the framework. Using those mathematical theories, one can derive error estimates of mode decomposition obtained by the present method and can obtain the phase-space reconstruction by using the leading modes of the decomposition. In this talk, we will show some results for some numerical and experimental datasets to validate the present method.

Naoto Nakano
JST PRESTO
Hokkaido University
n_nakano@math.sci.hokudai.ac.jp

CP10

Mild Solutions for Multi-Term Time-Fractional Impulsive Differential Equations with Non Local Initial Conditions

In this paper, we are concerned with the existence of the mild solutions for multi-term time-fractional differential equations with not instantaneous impulses. We obtain some sufficient conditions for the existence and uniqueness results using a generalization of the semigroup theory for linear operators, fractional calculus techniques and some suitable fixed point theorems under appropriate hypotheses. An example is also given to illustrate the applications of the established results.

Vikram Singh, Dwijendra N Pandey
IIT ROORKEE
vikramiitr1@gmail.com, dwij.iitk@gmail.com

CP11

Bifurcations of Invariant Tori in 3-Dimensional Piecewise Smooth Maps

Many physical systems are modeled by piecewise smooth maps. The theory of bifurcations in such maps is well developed in the context of 1D and 2D systems. In this work we investigate the dynamics of 3D piecewise smooth maps represented by a normal form, and report many atypical bifurcations that can happen in invariant closed curves. Some of these can be explained based on Lyapunov bundles and eigenvalues of saddle cycles, while some demand new insights.

Soumitro Banerjee
Indian Institute of Science education & Research,
Kolkata, India
soumitro.banerjee@gmail.com

Mahashweta Patra
Indian Institute of Science education & Research
Kolkata, India
mp12ip005@iiserkol.ac.in

CP11

Multiple Winner-Take-All Solutions in the Star-Like System of Phase Oscillators with Parameter Adaptation

We study a star-like system of phase oscillators with adaptation and apply this system for modelling of cognitive functions (e.g. visual search, attention focus, perceptual switching). The system includes a Central Oscillator (CO)

and multiple Peripheral Oscillators (POs). The oscillators are described as generalised Kuramoto type oscillators with parameter adaptation. The frequency of CO is adaptive and reflects the average frequency of POs. Connection strengths from POs to the CO are also adaptable. Interactions in the network are organised in such a way that POs compete for synchronisation with the CO. We use the bifurcation analysis to investigate the dynamical modes of the system. In particular, we are interested in winner-take-all regimes where one of the POs runs in-phase with the CO and the adaptation mechanism allows suppression of all other POs. In particular, the results of mathematical and computational studies have been accounted for reaction times in visual search experiments. It is postulated that those POs which are synchronised by the CO are included in the focus of attention. The probability for an object to be included in the focus of attention is determined by its saliency that is described in formal terms as the strength of the connection from the PO representing the target to the CO. It is shown that the model can reproduce reaction times in visual search tasks of various complexities.

Roman M. Borisyuk
School of Computing, Electronics and Math
Plymouth University
r.borisyuk@plymouth.ac.uk

Yakov Kazanovich
Institute of Mathematical Problems in Biology
Russian Academy of Sciences
kazanovichyakov@gmail.com

Oleksandr Burylko
Institute of Mathematics
Ukranian academy of Sciences
burylko@yahoo.co.uk

CP11

Explicit Symmetry Breaking and Hopf Bifurcations

Group theoretic means have been used before to study the effects of weak explicit symmetry breaking on steady state bifurcations of reaction-diffusion systems. We perform an analogous model-independent analysis of the effects of underlying anisotropies and inhomogeneities on systems undergoing pattern forming Hopf bifurcations.

Timothy K. Callahan
Embry-Riddle Aeronautical University
Department of Physics
callahat@erau.edu

CP11

On Stability of Coupled Systems with Delay and Hysteresis

In this work , two coupled systems with transmission and response delay along with memory of history leading to hysteresis are studied. Stability analysis is carried out. Numerical simulation of one illustrative problem is presented. Conditions for chaotic behavior are obtained.

Prasad G. Chhapkhane
Devchand College Arjunnagar
dir.casr@gmail.com; enq.casr@gmail.com

CP11

Detecting Phase Transitions in Collective Behavior Using Manifold's Curvature

If a given behavior of a multi-agent system restricts the phase variable to an invariant manifold, then we define a phase transition as a change of physical characteristics such as speed, coordination, and structure. We define such a phase transition as splitting an underlying manifold into two sub-manifolds with distinct dimensionalities around the singularity where the phase transition physically exists. Here, we propose a method of detecting phase transitions and splitting the manifold into phase transitions free sub-manifolds. Therein, we firstly utilize a relationship between curvature and singular value ratio of points sampled in a curve, and then extend the assertion into higher-dimensions using the shape operator. Secondly, we attest that the same phase transition can also be approximated by singular value ratios computed locally over the data in a neighborhood on the manifold. We validate the Phase Transition Detection (PTD) method using one particle simulation and three real world examples.

Kelum D. Gajamannage, Erik Bollt
Clarkson University
dineshhk@clarkson.edu, bolltem@clarkson.edu

CP11

Elliptic Bubbles in Moser's Quadratic Maps

In 1994 Moser generalized Hénon's two-dimensional quadratic maps to the four-dimensional, symplectic case. He showed that these maps can be written as the composition of an affine symplectic map with a quadratic shear or "jolt" map, or more explicitly, for $(x, y) \in R^2 \times R^2$, as

$$(x, y) = M(x, y) = (C^{-T}(-y + \nabla V(x)), Cx)$$

where C is a 2×2 matrix and V a cubic potential. The resulting family has six free parameters and two discrete moduli. We show that there is a codimension three bifurcation that corresponds to the simultaneous creation of four fixed points. Two of these can be center-center points and two center-saddles leading to the formation of a double-bubble of two-tori. We propose that this bifurcation is an organizing center for the dynamics of saddle-center bifurcations in 4D maps, and in particular is a normal form for the formation of accelerator modes in maps such as the Froeschlé family.

James D. Meiss
University of Colorado
Dept of Applied Mathematics
jdm@colorado.edu

Arnd Baecker
Institut für Theoretische Physik
TU - Dresden - Germany
baecker@physik.tu-dresden.de

CP12

Using Modeled Dynamics for the Control of Autonomous Vehicles

The primary goal of optimal planning and control algorithms is to lay out behaviors which conserve time and/or fuel, and then apply these findings to real-world systems.

Traditional, continuous-time control theory often has as a prerequisite that some technical assertions about the system dynamics be made, often in the form of explicit equations. For nonlinear and high-order systems, this can be a significant challenge. Another approach involves using orbit primitives combined with stochastic search algorithms, but these searches sample infeasible trajectories and are generally are not robust to model or state uncertainty. To address this, we wish to develop an intuitive, computationally efficient method that is robust to uncertainty. In this work, we present an approach to both the planning and control of lightweight ground vehicles that makes use of physical simulation and machine learning to perform these tasks concurrently and in real-time. As in our previous work [Keivan, Sibley; Realtime simulation-in-the- loop control for agile ground vehicles; TAROS 2014], we apply this physical simulator to test the feasibility of planned paths with respect to modeled vehicle dynamics and to generate control functions. The use of physical simulation within the planning and control loops provides an extremely dense feedforward model for vehicle and terrain dynamics. Furthermore, the approach allows for considering arbitrarily sophisticated models of these features.

Christoffer R. Heckman
Autonomous Robot & Perception Group
University of Colorado at Boulder
christoffer.heckman@colorado.edu

CP12

Analysis of Entropy Generation Due to Time Periodic Heating in a MHD Porous Enclosure

In this work, we analyze the hydro-magnetic mixed convection inside a nanofluid filled porous enclosure. The study focuses on the nanofluid flow behavior, heat transfer and entropy generation due to various flow governing parameters. A portion of side walls is thermally activated using time periodic heat sources. The effect of variable heat source length is investigated for optimum heat transfer with least entropy generation. The results are presented for a wide range of flow governing parameters including Grashof number, Hartmann number, Darcy number and volume fraction of nanoparticles. The thermodynamic optimization is discussed by using Nusselt number and entropy generation and the dominance of entropy generation due to heat transfer over entropy generation due to fluid friction and magnetic field is discussed with the help of Bejan number.

Sumit Malik
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
Indian Institute of Technology Roorkee
ssumitmalik@gmail.com

Ameeya Nayak
Indian Institute Of Technology Roorkee
ameeyakumar@gmail.com

CP12

A Model of Intergenerational Wealth Dynamics and Intergenerational Wealth Traps

An important question about the distribution of wealth is how the proportion of national wealth a person controls depends on the wealth of their parents. We develop a simple model of intergenerational wealth dynamics where individuals balance current consumption with investment in a single descendant. Investments then determine descendant wealth via a potentially nonlinear and discontinuous competitiveness function. From this model we demonstrate how to infer such a competitiveness function from investments, along with geometrical criteria to determine individual decisions. Finally, we investigate the stability of a wealth distribution, both to local perturbations and the introduction of new agents with no wealth. We prove that there is a fundamental relationship between high levels of individual investment levels and the existence of a wealth trap, which traps otherwise identical agents at a lower level of wealth.

Joel D. Nishimura
Arizona State University
joel.nishimura@asu.edu

CP12

Users Dynamics on Internet Platforms

I will discuss a dynamical system, which models two-sided Internet platform. The flow of the system corresponds to the volume of users from each side of the platform as a function of time. I will present theorems describing the long-term behavior of the volume of users, equilibriums and other characteristics. The results were obtained with the help of classical theory of dynamical systems. These results help to propose some strategies for platform's regulations that optimize the benefits of platform users and owners. Volume of users on platforms, equilibrium and other characteristics have mainly been studied with game-theoretic approach and from platform users point of view. However, growing number of Internet platforms with large amount of data allows to construct dynamical systems models and to study these models from the platform owners point of view. The dynamical system's approach to the study of two-sided platform allows natural generalization to multi-sided platforms (MSP), where one can utilize the theory of multidimensional dynamical systems, and obtain results for MSP with high number of dimensions.

Victoria Rayskin
Penn State University
vrayskin@gmail.com

CP12

The Emergence of Power-Law Scalings in Large-Scale Systems of Weakly Correlated Units

Characterizing the dynamical regime within which the brain operates is central to understanding its function. One attractive possibility is that neuronal networks operate at a critical state. This view is supported by experiments in neuronal cultures showing a power-law scaling of firing events size and duration, as well as the existence of a universal scaling function, in agreement with canonical models at criticality. In this talk, we will explore alternative phenomena accounting for such dynamics. First, coming back to a classical network of sparsely connected integrate-and-fire neurons network, we will show that similar statistics emerge in the network away from any critical transition and in regimes where there is no evidence of critical slowing down. Statistical physics theory indicates that for large network sizes, neurons in these networks are very weakly correlated, a decorrelation also observed in experiments. We will show that the power-law statistics and scalings can be directly associated to this low correlation, and persists in networks of independent Poisson units with a common firing rate. We will demonstrate that these statistics can rigorously be found in these systems, although microscopically, the system is stochastic. These results can reconcile apparently conflicting experimental observations such as the lack of evidence for SOC in neurons measured in the awake brain. They also put caution on the interpretation of scaling laws found in nature.

Jonathan D. Touboul
The Mathematical Neuroscience Laboratory
College de France & INRIA Paris
jonathan.touboul@college-de-france.fr

Alain Destexhe
CRNS Gif sur Yvette
alain.destexhe@unic.cnrs-gif.fr

CP12

Life-Detection and Through-Wall Imaging Using Ultra-Wideband Chaos Radar

Life-detection and through-wall radar technology, with the purpose of identifying vital signs and position of life-beings located behind an obstacle, has attracted great interest in various fields, such as urban warfare, antiterrorism, and rescue for earthquake, snow disaster or fire victims. In this paper, we propose an ultra-wideband (UWB) chaos radar for through-wall imaging and life-detection behind barrier. The UWB chaos radar transmits a wideband chaotic signal modulated by a single-tone sinusoidal wave. Using a split ring antenna integrated solid state sensor and lock-in amplifier, the radar can identify the frequency of breathing and heartbeat by detecting the phase information of the reflected sinusoidal wave from the human object. Further, human location is realized by correlating the chaotic echo signal with its delayed duplicate and combining the synthetic aperture technology. Experimental results demonstrate the proposed radar can detect the humans vital signs and location information through the obstacles with high range resolution and large detection range. The range resolution is 15 cm, benefiting from the 1 GHz-bandwidth of the chaotic signal. The detection range through 20 cm thick wall is about 5 m for the respiration signal detection and 3.4 m for the heartbeat signal detection.

Hang Xu
Taiyuan University of Technology
xuhang@tyut.edu.cn

Li Liu, Jianguo Zhang
Taiyuan University of Technology
Institute of Optoelectronic Engineering
liuli01@tyut.edu.cn, zhangjianguo@tyut.edu.cn

Jingxia Li
Taiyuan University of Technology
lijingxia@tyut.edu.cn

Bingjie Wang, Anbang Wang
Taiyuan University of Technology
Institute of Optoelectronic Engineering
wangbingjie@tyut.edu.cn, wanganbang@tyut.edu.cn

Yuncai Wang
Taiyuan University
Institute of Optoelectronic Engineering
wangyc@tyut.edu.cn

CP13

Deterministic Method to Identify Sparse Matrix of Parameters Based on Information Theory

In the modeling time-dependent data set with minimal dimension ODEs, recent researchers tend to consider the parameters matrix to be sparse with just a few elements that project the system dynamics with respect to basis functions. The uncertainty in constructing the parameters sparse matrix can lead to high error margins, being the optimally sparse representation from data may be highly over-sparsed, and consequently sparse optimization is brittle in the sense that significant system identification errors can result. In this paper, we introduce an information theoretic method to detect sparsity structure that may be sparse but not too sparse, just right, by a principle of causation entropy principle, which when then used as a mask in the estimation step, radically reduce the error in estimated parameters. Several examples are presented for low and high dimensions chaotic systems.

Abd Alrahman R. Almomani
Clarkson University
Department of Mathematics
almomaa@clarkson.edu

CP13

Least Action Methods and Noise Induced Transitions in Periodically-Forced Systems

We present a study of the metastability of periodic orbits for 1-D periodically forced systems perturbed by weak additive noise. It is well known that noise can introduce dramatic changes to the dynamics of the system, e.g. stochastic resonance, noise induced transitions between deterministic stable states etc. We ask the question: can noise induced transitions be completely understood using least-action principles and how do these results compare with classic results from large deviations? In particular, while pure noise induced transitions between metastable states occur on exponentially long time scales (Kramers rate) the frequency of the forcing introduces an additional time scale (inverse of the Floquet exponent) and a preferred phase of transition. Using least action principles, we show that the the preferred phase and expected time of transition depend crucially on the scaling of these parameters.

John Gemmer
Wake Forest University
Department of Mathematics
gemmerj@wfu.edu

Yuxin Chen
Northwestern University
yuxinchen2018@u.northwestern.edu

Alexandria Volkening
Division of Applied Mathematics
Brown University
alexandria_volkening@brown.edu

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

CP13

Perron-Frobenius Meet Monge-Kantorovich: A Set-Oriented Graph-Based Approach to Optimal

Transport

We study the problem of optimally steering measures in phase space for nonlinear systems. For discrete-time case, a switching approach to optimal transport is adopted. Here, dynamics are propagated by Perron-Frobenius operator, and the discrete-time perturbations are obtained as a result of Monge-Kantorovich optimal transport between intermediate measures on a graph. In the continuous-time case, we present optimal transport formulation of nonlinear systems with prescribed control vector fields. Our approach allows us to recover provably optimal control laws for steering agents from prescribed initial to final distributions in finite time for the case of control-affine systems, including the non-holonomic case. The action of the controlled vector field is approximated by a continuous-time flow on a graph obtained by discretizing the phase space. The problem is then reduced to a modified Monge-Kantorovich optimal transport on this graph via use of infinitesimal generators. We apply our method to examples from chaotic fluid dynamics and vehicle dynamics. By combining the infinitesimal-generator approach with the theory of optimal transport, we obtain a graph based version of optimal transport for nonlinear systems (OT-NS).

Piyush Grover
Mitsubishi Electric Research Laboratories
grover@merl.com

Karthik Elamvazhuthi
Arizona State University
karthikevaz@gmail.com

CP13

Forecasting Chaotic Business Cycles Perturbed by Noise

The failure of the Federal Reserve to timely raise the federal funds rate to its "normal' expectation causes chaos. By applying a Sprott nonlinear dynamical system, it becomes possible to forecast aperiodic business cycles. When the short-term interest rate is prudently targeted, the economy mean-reverts, like a Langevin equation perturbed by noise. Then business cycles no longer exist.

James M. Haley
Point Park Universtiy
kapucensko51@comcast.net

CP13

Entropy of Recurrence Plot Configurations

Recurrence plots are binary matrices where the trajectories of a dynamical system in the phase space are evaluated against another embedded trajectory. Due to the exponential increasing of the amount of data available due the advent of the information era, this graphical methodology based on visual qualification of patterns in the matrix has suffered natural limitations. Great part of these restrictions were overhauled by the recurrence quantification analysis (RQA). In this scenario the necessity on the development of suitable tools to quantify recurrence estates is a important topic. In our work we propose a new recurrence analysis tool based on the concept of information entropy, where micro-states are defined by all possible patterns displayed by a $K \times K$ size block of a recurrence plot (RP). Our methodology is a new RQA that evaluates the entropy of configurations of recurrences. This method has a weak dependence on parameters, is simple to evaluate, fixes several previous concerns regarding the traditional entropy of recurrences and reproduce classical results with advantages. In our conclusions we discuss some future perspectives, specially in the application to non-stationary data, real data and the evaluation of false neighbors.

Thiago L. Prado
Instituto de Engenharia, Ciência e Tecnologia
Universidade Federal dos Vales do Jequitinhonha e Mucuri
thiago.prado@ufvjm.edu.br

Gilberto Corso
Departamento de Biofísica e Farmacologia
Universidade Federal do Rio Grande do Norte
gfcorso@gmail.com

Gustavo Lima
science and technology school
Federal University of Rio Grande do Norte
guzampier76@gmail.com

Sergio Lopes
Departamento de Física
Universidade Federal do Paraná
lopes@fisica.ufpr.br

CP14

Coupled System of Electrical Oscillators and Their Solutions in Perspective of Fractional Derivatives

We study the system of fractional order coupled oscillators associated with electric circuit in view of various types of fractional derivatives. Further, the analytical solutions of these equations have been established using tools of fractional calculus. For some types of fractional derivatives, the solutions have been found very close to classical solutions as the order of fractional derivative approaches to two.

Naseer Ahmad Asif
University of Management and Technology, Lahore, Pakistan
naseerasif@yahoo.com

Muhammad Imran Jamil
University of Management and Technology
Lahore, Pakistan
mimranjamil@hotmail.com

CP14

Existence Results for Two-Term Time Fractional Differential Equations with Nonlocal Conditions

In this paper, we employ the method of lower and upper solutions coupled with the monotone iterative technique to set up the existence of the mild solutions for the following two-term time fractional differential equations with nonlocal conditions in a Banach space X

$$\begin{cases} D^{\alpha+1}u(t) + \eta D^{\beta}u(t) - Au(t) = f(t, u(t)), & t \in I = [0, T],\ T > 0,; \\ u(0) = u_0 + g(u), \quad u_t(0) = u_1 + h(u), \end{cases}$$

where $0 < \alpha \leq \beta \leq 1$, D^{α} denotes the Caputo fractional derivative of order α. $\eta \geq 0$. $A : D(A) \subset X \to X$ is a closed linear operator which generates a strongly continuous family of bounded linear operators on X. Functions $f : I \times X \to X$, $g : X \to X$ and $h : X \to X$ are given

functions satisfies monotonicity and measure of noncompactness conditions. u_0, $u_1 \in X$. At last, an example is given to show the availability of main results.

Renu Chaudhary, Dwijendra N Pandey
IIT ROORKEE
rrenu94@gmail.com, dwij.iitk@gmail.com

CP14

Inverse Problem for Dynamical Systems with Uncertain Data

The problem of estimation of parameters of a dynamical system from discrete data can be formulated as the problem of inverting the map from the parameters of the system to points along a corresponding trajectory. Presented will be an overview of recent results in this area, specifically, (i) conditions for identifiability of linear and linear-in-parameter systems from a single trajectory, (ii) analytical and numerical estimates of the maximal permissible uncertainty in the data for which the qualitative features of the inverse problem solution for linear systems, such as existence, uniqueness, or attractor properties, persist, and (iii) techniques for parameter estimation of ensemble models, i.e., models of deterministic processes with uncertain parameters.

David Swigon
Department of Mathematics
University of Pittsburgh
swigon@pitt.edu

Shelby Stanhope
Temple University
stanhope@temple.edu

Jonathan E. Rubin
University of Pittsburgh
Department of Mathematics
jonrubin@pitt.edu

CP14

Understanding Mixing Processes by Transfer Operator

Industrial and chemical mixing mixing processes of various kinds occur throughout nature and are vital in many technological applications. In the context of discrete dynamical systems, the transfer operator approach has been shown as a powerful tools from both theoretic and numerical viewpoint. In this talk, I will use a toy model (i.e., the one dimensional stretch and fold map) as an example to provide a brief introduction on the relationships between the spectral properties of the associated transfer operator and the estimations of the optimal mixing rate of the mixing process. Moreover, I will address how the optimal mixing rate varies according to the stretch and fold map has "cutting and shuffling' behaviour (i.e., composing with a permutation). If time permits, I will also talk about how to interpret this problem to the eigenvalue estimations for the Random bi-stochastic matrices (free probability theory) and the locations of poles of the dynamical zeta function

Yiwei Zhang
huazhong university of science and technology
yiweizhang@hust.edu.cn

MS1

Isochrons for Saddle-Type Periodic Orbits in Three-Dimensional Space

Many physical systems feature stable oscillations. Such systems are often modelled by ordinary differential equations, such that the stable oscillation is represented by an attracting periodic orbit. Each point in the basin of attraction of this periodic orbit will converge to it with a particular phase; all points that synchronise with the same phase are said to lie on an isochron. Isochrons are smooth manifolds that have one dimension less than that of the basin of attraction, and the family of isochrons associated with all of the phase points which constitute the periodic orbit make up that entire basin. Isochrons are used in applications to study the effects of a perturbation, in terms of the relative phase at which the perturbed point returns to the periodic orbit. There are very few systems for which isochrons can be computed analytically; as soon as the dynamics become interesting one has to make use of numerical methods. Previously, methods to compute these isochrons have focused on planar systems. I will present an extension of this method to compute isochrons for both orientable and non-orientable saddle-type periodic orbits in three-dimensions which will lie on that periodic orbit's two-dimensional invariant manifolds. This constitutes a first step towards computing isochrons in higher dimensions, and showcases the intricacies of their geometry.

James Hannam
Department of Mathematics
University of Auckland
james.hannam@auckland.ac.nz

Hinke M. Osinga, Bernd Krauskopf
University of Auckland
Department of Mathematics
H.M.Osinga@auckland.ac.nz, b.krauskopf@auckland.ac.nz

MS1

Time-Optimal Control of Biological Oscillators using Isochrons and Isostables

We have developed an optimal control algorithm to change the period of a periodic orbit using a minimum energy input, which also minimizes the controlled trajectory's transversal distance to the uncontrolled periodic trajectory. Our algorithm uses the augmented phase reduction, a recently developed two-dimensional reduction technique based on both isochrons and isostables. To demonstrate the effectiveness of the algorithm, we apply it along with a previous optimal control algorithm based on standard phase reduction (one-dimensional reduction based on isochrons) to biological dynamical systems where a change in time period of the periodic orbit holds practical relevance. We show that the control algorithm based on the augmented phase reduction is effective even when a large change in time period is required or when the nontrivial Floquet multiplier of the periodic orbit is close to one; in such cases, the control algorithm based on the standard phase reduction fails.

Bharat Monga
Mechanical Engineering
UC Santa Barbara
monga@umail.ucsb.edu

Jeff Moehlis
Dept. of Mechanical Engineering
University of California – Santa Barbara
moehlis@engineering.ucsb.edu

MS1

Isostable Reduction for Stable Limit-Cycling Systems

A systematic reduction method of the limit-cycling dynamics using the isochrons has been a powerful framework for analyzing rhythmic activities in many fields. Recently, the Koopman operator-theoretic approach has revealed that the properties of the transient dynamics around attractors can be well-characterized by the notion called isostables. We have developed an isostable reduction method and a bi-orthogonalization method to obtain the infinitesimal isostable response curves for stable limit cycle oscillators. The validity of the proposed method is confirmed by comparing the results to direct numerical simulations of the full dynamical system. We also illustrate the utility of the proposed reduction framework by estimating optimal injection timing of external input that efficiently suppresses deviations of the system state from a limit cycle.

Sho Shirasaka, Wataru Kurebayashi
Tokyo Institute of Technology
shirasaka.s.aa@m.titech.ac.jp, wkurebayashi@gmail.com

Hiroya Nakao
Graduate School of Information Science and Engineering,
Tokyo Institute of Technology
nakao@mei.titech.ac.jp

MS1

Defining the "Phase" of a Stochastic Oscillator

A stable, finite-period limit cycle in a deterministic system admits a flow-invariant system of Poincaré sections with the properties (i) all trajectories initiated on a given leaf converge to a common trajectory on the limit cycle; (ii) all trajectories initiated on a given leaf pass through the same leaf after an interval equalling one period. The leaves are the isochrons, and the timing of their movement defines the asymptotic phase of points converging to the limit cycle. In a Markovian stochastic setting, two generalizations of the asymptotic phase and the isochron foliation have been proposed, one based on a spectral decomposition of the generator of the Markov process, the other on a foliation defined by a uniform mean first passage time property. We will discuss the (non)equivalence of these two generalizations of the phase of a noisy oscillator.

Peter J. Thomas
Case Western Reserve University
pjthomas@case.edu

Alexander Cao
Department of Mathematics, Applied Mathematics, and Statisti
Case Western Reserve University
axc487@case.edu

Benjamin Lindner
Bernstein Center for Computational Neuroscience Berlin
Department of Physics, Humboldt University, Berlin, Germany
benjamin.lindner@physik.hu-berlin.de

MS2

Pairwise Network Information and Direct Connectivity

From interacting populations of earthquake faults to the nerve cells in the brain, many complex systems can be represented as a collection of coupled dynamical units. In many practical applications, however, this network structure cannot be directly observed or reliably inferred from the observed activity by current methods. Instead, effective or functional networks are then considered: units are connected by a link if their relationship satisfies some criteria. The idea that a given system can be well described by a functional network, and the pairwise measurements they are built from, is a simplifying assumption typically used in these cases. Here, we introduce a novel, efficient, and general method to (i) quantify how good the assumption of pairwise interactions is, and (ii), if it is a good assumption, to reliably infer the backbone of the *direct* network connectivity between the interacting units. At the core, our method is a novel entropy maximization scheme that is based on conditioning on entropies and mutual informations. We establish that our method is particularly well suited for the typical case of large nonlinear systems where the dynamical units have more than two states and in the undersampled regime, both situations where previous methods failed. The advantages of the proposed method are documented using phase oscillator networks and a resting-state human brain network as generic relevant examples.

Jaroslav Hlinka
Institute of Computer Science
Academy of Sciences of the Czech Republic
hlinka@cs.cas.cz

Joern Davidsen, Elliot Martin
Complexity Science Group
University of Calgary
joern.davidsen@ucalgary.ca, kryptec@gmail.com

MS2

Inferring Directed Interactions from Data: An Overview

Complex networks are increasingly used in various scientific fields to characterize spatially extended dynamical systems. The reliable inference of, in particular, directed networks from empirical data, however, continues to represent a challenging issue. This talk provides an overview of analysis techniques that are frequently used to infer directed interactions from pairs of time series, discusses their pros and cons, and points to possible improvements.

Klaus Lehnertz
Department of Epileptology
University of Bonn, Germany
klaus.lehnertz@ukb.uni-bonn.de

MS2

Tackling Indirect Directional Couplings in Large Oscillator Networks: Partial Or Non-Partial Phase Analysis?

We investigate the relative merit of the evolution map approach and its partialized extension for inferring directional couplings in complex networks of weakly interacting dynamical systems from multivariate time-series data. We simulate several experimental situations and study to which extent the approaches correctly infer the network topology in the presence of indirect directional couplings in coupled model systems. In addition, we investigate whether the partialized extension allows for additional or complementary indications of directional interactions in multichannel electroencephalographic recordings, for which both direct and indirect directional couplings can be expected. Overall, our findings indicate that particularly in larger networks the partialized extension does not provide information about directional couplings extending the information gained with the evolution map approach.

Thorsten Rings
Dept. of Epileptology
University of Bonn, Germany
thorsten.rings@uni-bonn.de

Klaus Lehnertz
Department of Epileptology
University of Bonn, Germany
klaus.lehnertz@ukb.uni-bonn.de

MS2

Coupling Function Decomposition

Interactions of dynamical systems are often assessed only as the net coupling between the systems. Here we show how one can go beyond this and decompose the net into direct and indirect coupling components. By modelling the interacting dynamical systems we decompose the net coupling function into its functional components which are partially grouped as unities that constitute the direct from one system, or the common indirect influence from both of the systems. The method is presented by Fourier coupling function decomposition of phase dynamics from interacting oscillators. The coupling function components are estimated with dynamical Bayesian method for inference of time-evolving dynamics in presence of noise. The technique is used to determine the effect of general anaesthesia on the neural-cardio-respiratory coupling function components.

Tomislav Stankovski
Skopje, Macedonia
Ss. Cyril and Methodius University, Skopje, Macedonia
t.stankovski@ukim.edu.mk

MS3

Networks of Networks: Dispersal induced Supersaturation in Meta-Communities

Metacommunity models describe ecological systems consisting of several patches or habitats in which several populations interact with each other as competitors or via predator-prey relationships in form of food webs. Those food webs are interconnected by migration corridors. Such metacommunities can be considered as networks of networks. Competition among species for resources is in most ecological models determined only by one limiting resource. We study metacommunities in which multiple resource limitation is taken into account leading to non-equilibrium coexistence of species. For a multi-species community, *supersaturation* is a state of coexistence, where the number of species competing for resources exceeds the number of limiting resources. In this work, we study the interplay between resource conditions in the patches and dispersal structure. Specifically, we analyze to what extent dispersal, i.e. coupling in the network of habitats/communities, can support supersaturation in the network of networks even in the case when not all patches provide resource conditions in which more species than limiting resources can survive. Our principle result states that the lower bound on the initial fraction of supersaturated patches needed to obtain supersaturation in the whole network, can be optimized by dispersal structure. Further, we identify crucial links in the dispersal topology which, if broken, lead to the collapse of global supersaturation.

Anshul Choudhary
Universität Oldenburg
anshul.choudhary@uni-oldenburg.de

Ramesh Arumugam
{Department of Mathematics, Indian Institute of Technology,
Ropar, India
aramesh@iitrpr.ac.in

Partha Sharathi Dutta
Department of Mathematics, Indian Institute of Technology,
Ropar, India
parthasharathi@iitrpr.ac.in

Ulrike Feudel
University of Oldenburg
ICBM, Theoretical Physics/Complex Systems
ulrike.feudel@uni-oldenburg.de

MS3

Indirect Targeting in Networks

Traffic jams, genetic diseases, financial crises, ecosystem collapse. These are just a few examples of far-reaching disruptions in complex systems that can nonetheless be caused by abnormal activity in only a handful of componentsroads, genes, banks, or invasive species. Yet quite often, remedying these system-level failures is intractable precisely because the few malfunctioning components are those most unamenable to direct intervention. Here, we develop a network solution to this broadly significant problem. By exploiting the phase space structure of the systems (nonlinear) dynamics, we show that it is in general possible to manage, activate or even disable a node indirectly, via manipulations confined to the other nodes in the network. Using food-web and boolean networks as model systems, we demonstrate that this concept of indirect targeting could, for example, allow elimination of invasive species by acting on the populations of other (indigenous) species, or toggling the activity of disease-causing genes by modulating other, less entrenched components. Moreover, our simulations show that these feats can often be accomplished by acting on only a small minority of the rest of the network, suggesting a high potential for indirect intervention in real systems. Altogether, these results provide a path forward for the design of focused, minimally-intrusive control interventions that can tune otherwise inaccessible nodes.

Sean P. Cornelius, Adilson E. Motter
Northwestern University
spcornelius@gmail.com, motter@northwestern.edu

MS3

**Evaluating the Sensitivity of Dynamical Systems to

Interaction Network Topology

A network's reliability was defined by Shannon and Moore in terms of the probability that the dynamics of a specific dynamical system defined on the network exhibits specific properties. A straightforward extension of this concept to general network dynamical systems provides a useful paradigm for studying the sensitivity of dynamics to network topology. An understanding of this sensitivity can be used for characterization or topological control of the dynamical system. The discrete nature of a network introduces issues beyond well-known ones such as local vs. global sensitivity. In particular, evaluating the network reliability exactly is known to be NP-hard in most cases. Approximating it is also computationally hard. Moreover, approximating sensitivity to network topology requires detecting very small differences in reliability. We define evaluating sensitivity to network topology as a formal optimization problem, introduce two constraints that permit a greedy approach, and exhibit a provably efficient, computationally stable algorithm for finding approximate solutions with controllable error. We compare the algorithm's performance with that of several heuristics that have been proposed for related problems such as finding community structure.

Stephen Eubank
Biocomplexity Institute of VA Tech
seubank@vbi.vt.edu

Yihui Ren
Virginia Bioinformatics Institute
yren2@vbi.vt.edu

Madhurima Nath
Physics Dept.
Virginia Tech
nmaddy@vbi.vt.edu

MS3

Transitivity Reinforcement in Co-Evolving Network Models

One of the fundamental structural property of complex networks is transitivity. Its influence in models with co-evolving (adaptive) network topology is not well explored. Existing coevolving network models use rewiring rules that randomize away this property. We will introduce a model for epidemic spread and a model for opinion formation, which explicitly reinforces and maintains transitivity. We will discuss impacts of reinforcement of transitivity in these two models. We will illustrate a semi-analytic method, approximate master equation (AME) for studying these models. And show that this technique can predict the dynamical behavior of these models for various parameter settings.

Nishant Malik
Department of Mathematics
Dartmouth College
nishant.malik@dartmouth.edu

Hsuan-Wei Lee
Department of Sociology, University of Nebraska Lincoln
waynelee1217@gmail.com

Bill Shi
UNIVERSITY OF CHICAGO
bill10@uchicago.edu

Peter J. Mucha
University of North Carolina Chapel Hill
mucha@unc.edu

MS4

Spectral Notions of Aperiodic Order

The characterization of aperiodic structures usually employs spectral notions and properties. In particular, this applies to Fourier analysis in the form of diffraction measures. These are directly linked to experimental observations, for instance in the structure analysis of quasicrystalline materials. While diffraction provides information about the order in a system, we are still far from any classification of systems displaying some form of long-range order. From a mathematical perspective, many of the aperiodic structures that are considered give rise, under translation action, to ergodic dynamical systems. There is then a natural spectral measure associated to this dynamical system, which is the dynamical spectrum. While the connection between the dynamical and diffraction spectra for the pure point case has been known and used for a while, the more general relationship between these spectral notions has only been elucidated recently. The talk will discuss the two spectral notions and explain their relation by means of simple explicit examples.

Uwe Grimm
Department of Mathematics & Statistics
The Open University
u.g.grimm@open.ac.uk

MS4

Two Decades of Multiple Scale Patterns: From Faraday Waves to Soft Quasicrystals

Abstract Not Available At Time Of Publication.

Ron Lifshitz
School of Physics and Astronomy
Tel Aviv University
ronlif@tau.ac.il

MS4

Growth Rules for Icosahedral Quasicrystalline Tilings

Tiling models provide a useful conceptual framework for addressing fundamental questions about quasicrystal stability and growth. The physical processes that produce highly ordered icosahedral samples, both manufactured and naturally occurring, suggest the importance of growth kinetics in the formation of icosahedral quasicrystals. Thus we would like to know whether perfectly ordered icosahedral quasicrystals can, in principle, be reached through a kinetic growth process without requiring annealing of phason fluctuations. A recently developed growth algorithm based exclusively on local rules for sequential addition of tiles to a cluster succeeds in producing an icosahedral quasicrystal with a vanishing density of defects, but only when the growth proceeds from a suitable seed containing a defect. The same principles of growth apply to two different tilings, Ammann's rhombohedral tiling and Socolar and Steinhardt's zonohedral tiling. These two tilings are very closely related, the vertices of the latter being a subset of vertices of the former. Nevertheless, the geometry of the growing clusters is quite different in the two cases. I will explain what we know about the two tilings, the nature of the

growth algorithm, and the features of the seeds required to initiate infinite growth. [Work done in collaboration with C. Hann, P. Steinhardt, and X. Ma.]

Joshua Socolar
Duke University
Physics Department
socolar@phy.duke.edu

MS4

Spatially Localized Quasicrystals

The formation of quasicrystalline structures arising in diverse soft matter systems such as dendritic-, star-, and block co-polymers can be analysed using a phase field crystal model. Direct numerical simulations combined with weakly nonlinear analysis highlight the parameter values where the quasicrystals are the global minimum energy state and help determine the phase diagram. By locating parameter values where multiple patterned states possess the same free energy (Maxwell points), we obtain states where a patch of one type of pattern (for example, a quasicrystal) is present in the background of another (for example, the homogeneous liquid state). In a bifurcation diagram such localized states fall on solution branches that snake and these can be obtained through numerical continuation. From the bifurcation diagram, we locate dynamically unstable spatially localized patterns from which quasicrystals can be grown in experiments.

Priya Subramanian
University of Leeds
P.Subramanian@leeds.ac.uk

Andrew Archer
Department of Mathematical Sciences
Loughborough University
a.j.archer@lboro.ac.uk

Edgar Knobloch
University of California, Berkeley -
Nonlinearity, Institute of Physics
knobloch@berkeley.edu

Alastair M. Rucklidge
Department of Applied Mathematics
University of Leeds
A.M.Rucklidge@leeds.ac.uk

MS5

Variational Approach for Estimation of Parameters in Hodgkin-Huxley Models

We use biophysically motivated Hodgkin-Huxley (HH) models, experimentally obtained recordings of the voltage of avian HVCI neurons and mouse CA1 neurons, and our data assimilation approach to infer the full set of parameters reproducing the observed waveform information. Our data assimilation algorithm formulates the problem of inferring parameters and unknown states in a dynamical model as a path integral. We utilize Laplace's method to approximate the integral and obtain our estimates, and we compare predictions of the model forward in time with data to validate our estimates.

Daniel Breen
Department of Physics
UC San Diego
dlbreen@physics.ucsd.edu

MS5

Feature-Based Parameter Estimation in a Model of Anterior Pituitary Cell Electrical Activity

Electrical activity of endocrine pituitary cells is highly heterogeneous in individual cells and across populations. This motivates fitting of models to single cells, but makes fitting directly to voltage trace data difficult. We take the approach of reducing data to distributions of features that represent the cell's spontaneous and stimulated activity, then fitting model parameters based on these features. Simulated experimental data is used to suggest stimuli and associated features that help to constrain the model parameters. The feature-based optimization is accelerated using a programmable graphics processing unit (GPU). When coupled with the dynamic clamp technique, this approach can be used to rapidly fit a model to an individual cell, then test model predictions in the same cell.

Patrick A. Fletcher
Laboratory of Biological Modeling
National Institutes of Health
patrick.fletcher@nih.gov

MS5

Markov Chain Monte Carlo Estimation of Conductance-Based Model Parameters

Formulating models of cellular electrical activity from biophysical principles introduces numerous parameters: membrane capacitance, maximal ion channel conductances, current reversal potentials and time constants, etc. Traditionally, laborious experimental manipulations designed to isolate each parameter have been used to calibrate such models. Here, we consider finding an optimal fit of model parameters to limited data, such as the membrane's current-voltage relation or voltage response to a varying applied current, using a Markov Chain Monte Carlo approach. Such a stochastic optimization procedure has the advantage of fitting numerous parameters while potentially avoiding convergence to local extrema of a chosen cost function.

Joseph Mckenna
Department of Mathematics
Florida State University
jmckenna@math.fsu.edu

MS5

Data Assimilation and Electrophysiological Modeling of Mammalian Circadian Clock Neurons

Recently there has been interest in the application of data assimilation tools to the improvement of neuronal models. Often, the only data one has access to is the measured voltage from a current-clamp experiment with a prescribed injected current. Our work aims to improve understanding of the impact that injected current stimuli has on the identifiability of parameters in a neuronal model. Parameter estimation results will be shown from 4D-variational data assimilation (4D-var) and an Unscented Kalman Filter (UKF). We will test the performance of characteristic currents, including steps, ramps, and chaotic currents. The ability of these various stimulus protocols to enable state and parameter estimation will be assessed using simulated data from the Morris-Lecar model and a biophysical model of mammalian circadian clock neurons in the suprachiasmatic nucleus.

Matthew Moye
Department of Mathematical Sciences
New Jersey Institute of Technology
mjm83@njit.edu

MS6

Effective Dynamics of Multiple Molecular Motors

The transport of cargo attached to multiple motors may be modeled as a system of stochastic differential equations. Motors may switch between attached and detached states, each of which having separate equations for determining motor positions. In this talk, we derive effective velocities and diffusions for such motor systems. This involves law of large numbers and central limit theorem arguments taken from renewal theory and multiscale averaging techniques. Identical motor systems and nonidentical systems, both cooperative and tug of war, will be considered. Results will be compared with experimental observations and other models.

Joe Klobusicky
Geisinger Health Systems
klobuj@rpi.edu

MS6

Biological Applications of Diffusion in a Randomly Switching Environment

A number of diverse biological systems involve diffusion in a randomly switching environment. For example, such processes arise in brain biochemistry, cell signaling, insect respiration, and intracellular virus trafficking. Mathematically, these processes often involve imposing randomly switching boundary conditions on either a PDE or SDE. In this talk, we will describe the mathematical tools for analyzing these systems and show how this analysis can yield new biological insight.

Sean Lawley
Duke University
lawley@math.utah.edu

MS6

A Non-Markov Model for Swimming Droplets

I present a model for analyzing self-propelling droplets that interact through their created concentration gradients. This non-Markov stochastic model shows the existence of constant velocity solutions and super-diffusive scalings. A tunable parameter controls the history of interaction, allowing the system to go from having complete memory to behaving like interacting electrostatic potentials.

Katherine Newhall
Dept. of Mathematics
University of North Carolina at Chapel Hill
knewhall@unc.edu

MS7

Exploring Microstructural Mechanisms for Tailoring Effective Material Nonlinear Response

Material nonlinearity has been shown to enable a wide capacity for stress wave tailoring, however, the choices of available nonlinearities have hitherto been highly limited. Microstructural geometric nonlinearities, such as those present in granular media, are one approach to creating effective material nonlinearities. In this presentation, we will discuss recent progress in our exploration of how the microstructural geometry of mechanical metamaterials can be tailored to enable variable effective material nonlinearities, and present a categorization of several major underlying mechanisms. Our study involves microstructure design using finite element modeling, and experimental validation via mechanical testing of additively manufactured metamaterials. This work opens the door for the experimental realization of a wide class of theoretically proposed nonlinear dynamical systems.

Nicholas Boechler
University of Washington
Department of Mechanical Engineering
boechler@uw.edu

MS7

Impact Dispersion Using 2D and 3D Composite Granular Packing

We present a study of efficient dispersion of an impact onto structured and potentially scalable granular beds. We use discrete element method based dynamical simulations of shock wave propagation and dispersion in 2D and 3D arrangements of granular spheres. The spheres are geometrically packed in a nested columnar structure, which leads to the severe attenuation and spreading of the incident energy within the structure. We further show that by incorporating inhomogeneity in material properties, or by introducing layers of a dissimilar material in the middle of the arrangement, impact mitigation can be enhanced significantly. Such an arrangement can therefore be useful in the design of effective impact decimation systems. Using a 2D arrangement we first show the basic idea behind impact dispersion in such an arrangement. With this understanding the system is scaled to 3D. The influence of the system size and material properties on the wave propagation within the packing is also presented.

Surajit Sen
SUNY Buffalo
sen@buffalo.edu

Mukesh Tiwari
Ambani Institute of Information and Communication Technology
mukesh_tiwari@daiict.ac.in

T R Krishna Mohan
Centre for Mathematical Modelling and Computer Simulations
kayemtr@gmail.com

MS7

Topological Sound and Odd Viscosity in Chiral Active Materials

Active materials are composed of interacting particles individually powered by motors. In this talk, we focus on chiral active materials that violate parity and time reversal symmetry. First, we show how to generate topological sound in fluids of self-propelled particles exhibiting a spontaneous chiral active flow under confinement. These topological sound modes propagate unidirectionally, without backscattering, along either sample edges or domain walls and despite overdamped particle dynamics. Next, we discuss an exotic transport coefficient characteristic of quantum Hall fluids, called odd viscosity, which controls the hydrodynamics of classical fluids composed of active rotors. This odd viscosity couples pressure to vorticity leading to transverse flow in Burgers shocks. We envision that such transverse response may be exploited to design self-assembled hydraulic cranks that convert between linear and rotational motion in microscopic machines powered by active rotors fluids.

Vincenzo Vitelli
Associate Professor,Soft Condensed Matter Theory Group
Instituut-Lorentz, Universiteit Leiden
vitelli@lorentz.leidenuniv.nl

MS7

Formation of Rarefaction Waves and Reverse Shocks in Strain-Softening Lattices

We investigate the feasibility of forming shocks and rarefaction waves in nonlinear mechanical metamaterials. As a prototypical system, we assemble two types of mechanical metamaterials: (i) 1D and 2D square lattices made of thin-walled elliptical unit cells, and (ii) 3D structures based on volumetric origami cells, e.g., Tachi Miura Polyhedron and Kresling origami. These lattices exhibit controllable strain-softening behavior, which can be tuned by modifying their initial geometrical and loading conditions. Preliminary results based on computational simulations show their unique mechanisms of impact mitigation based on the formation of rarefaction waves and reverse shocks. These numerical results are complemented by analytical predictions based on quasi-continuum approximation of a generalized inviscid Burgers model.

Jinkyu Yang
University of Washington
jkyang@gmail.com

Hiromi Yasuda, Hryunryung Kim
Department of Aeronautics and Astronautics
University of Washington
hiromy@uw.edu, hryungk@gmail.com

Christopher Chong
Bowdoin College
cchong@bowdoin.edu

Panayotis Kevrekidis
University of Massachusetts
kevrekid@math.umass.edu

MS8

Data-Driven Techniques for Modeling, Control and Sensor Placement

We present a cluster-based ROM (CROM) strategy to distill nonlinear mechanisms in an unsupervised manner directly from data. This strategy uses cluster analysis to partition snapshot data into a small number of representative states in the state space. The transitions between these states are then dynamically modeled as a Markov process, which is related to approximating the Perron-Frobenius operator. CROM has potential applications for the systematic identification of physical mechanisms of complex dynamics, for the identification of precursors to desirable and undesirable events, and for flow control design exploiting nonlinearities.

Eurika Kaiser
University of Washington
eurika@uw.edu

Bernd Noack
LIMSI-CNRS
Technical University Braunschweig
bernd.noack@limsi.fr

Andreas Spohn
Institute PPRIME, ENSMA
andreas.spohn@ensma.fr

Robert K. Niven
The University of New South Wales, Australia
r.niven@adfa.edu.au

Louis N. Cattafesta
FCAAP, Florida State University, USA
cattafes@gmail.com

Marek Morzynski
Poznan University of Technology
marek.morzynski@put.poznan.pl

Steven Brunton, Bingni W. Brunton
University of Washington
sbrunton@uw.edu, bbrunton@uw.edu

Nathan Kutz
University of Washington
Dept of Applied Mathematics
kutz@uw.edu

MS8

Space-Time Computational Methods for Coherent Sets

The decomposition of the state space of a dynamical system into metastable sets is important for understanding its essential macroscopic behavior. The concept is quite well understood for autonomous dynamical systems, and recently generalizations appeared for non-autonomous systems: coherent sets. Aiming at a unified theory, in this talk we first present connections between the measure-theoretic autonomous and non-autonomous concepts. We will do this by considering the augmented state space. Second, we introduce a data-based method to compute coherent sets. It uses diffusion maps for spatio-temporal trajectory data, and it is consistent in the infinite-data limit with the widely-used transfer operator approach for coherent sets.

Peter Koltai
Free University Berlin
peter.koltai@fu-berlin.de

MS8

Trajectory-based Computational Analysis of Coherent Structures in Flows

The notion of coherence in time-dependent dynamical systems is used to describe mobile sets that do not freely mix with the surrounding regions in phase space. Recently, different computational methods have been proposed to identify coherent behavior in flows directly from Lagrangian trajectory data, such as obtained from particle tracking

algorithms. In this context, spatio-temporal clustering algorithms have been proven to be very effective for the extraction of coherent sets from sparse and possibly incomplete trajectory data. Inspired by these recent approaches, we consider an unweighted, undirected network, which is constructed based on relative trajectory positions. Classical graph algorithms are then employed to analyze the network properties and to extract coherent behavior of the underlying flow. The proposed method is very fast to run, and we demonstrate that is produces useful results in a number of example systems. Furthermore, we point out theoretical links to other approaches.

Kathrin Padberg-Gehle
Institute of Scientific Computing
TU Dresden
padberg@leuphana.de

MS8

Numerical Studies of Turbulent Rayleigh-Bénard Convection Flows in Large-aspect-ratio Cells

We present results of three-dimensional direct numerical simulations of Rayleigh-Benard convection in flow domains with side lengths that are significantly larger than the height of the layer. In the turbulent flow regime, time-averaged mean velocity patterns get organized in roll patterns that are similar to the weakly nonlinear regime right above the linear stability threshold of convection. These patterns are found to evolve very slowly with respect to time on the largest horizontal scales. First results of a parametric study at different Prandtl and Rayleigh numbers are presented in which we determine the typical correlation scales of the patterns and their contribution to the global transfer of heat by means of Lagrangian methods.

Joerg Schumacher
Technische Universitat Ilmenau
Institute of Thermodynamics and Fluid Mechanics
joerg.schumacher@tu-ilmenau.de

MS9

Effect of Unstable Quasiperiodic Orbits on Heavy-Duty Milling Operation

We present theoretical and experimental study how unstable quasiperiodic oscillations can affect regenerative time-periodic milling processes. Due to the nonlinearity in the cutting force characteristics, subcritical branch emerges from the Hopf bifurcation point of the periodic solution correspodning to the stationary cutting process. This branch was calculated by numerical continuation till the point where the corresponding solution grazes the periodic switching surfaces originated from cutting edge flyover. Also, results were compared with experiments performed in heavy-duty milling machine equipped with internal inertial drive. Starting with stable stationary cutting, perturbation was introduced for several revolution of the milling tool then self-excitation was formed freely. By varying the driving current of the inertial actuator, the size of the domain of attraction was determined.

Zoltan Dombovari
Dynamics and Control, IK4Ideko
20870 Elgoibar, Basque Country, Spain
dombovari@mm.bme.hu

Jokin Munoa
Ideko Research Alliance IK4
Danobat Group
jmunoa@ideko.es

MS9

Analytical Results in Nonlinear Dynamics of Turning

Nonlinear dynamics and bifurcation analysis of regenerative machine tool vibrations in turning are considered. The global dynamics of turning involves switching between two vector fields that represent metal cutting and free oscillations of the tool. The dynamics during cutting is governed by a delay-differential equation, which is typically nonlinear through the characteristics of the cutting force. Machine tool vibrations are associated with the loss of stability of the equilibrium. The stability is lost via Hopf bifurcation, which is typically subcritical and implies the onset of unstable periodic solutions. When the amplitude of the periodic oscillations gets so large that the tool loses contact with the workpiece, a nonsmooth fold bifurcation takes place that gives rise to a large-amplitude attractive solution. The large-amplitude solution is called chatter: it is a complicated (sometimes even chaotic) motion that involves intermittent loss of contact between the tool and the workpiece. At the intersections of the stability boundaries, double Hopf bifurcations take place. Here, the dynamics is more complicated: in addition to two unstable periodic solutions and a stable chaotic one, an unstable quasi-periodic solution might also coexist with the linearly stable equilibrium. In this work, analytical methods are presented to approximate the arising periodic and the quasi-periodic solutions, and the region of coexistence is predicted by simple closed-form formulas.

Tamas G. Molnar, Zoltan Dombovari
Department of Applied Mechanics
Budapest University of Technology and Economics
molnar@mm.bme.hu, dombo@mm.bme.hu

Tamas Insperger
Budapest University of Technology and Economics
Department of Applied Mechanics
insperger@mm.bme.hu

Gabor Stepan
Department of Applied Mechanics
Budapest University of Technology and Economics
stepan@mm.bme.hu

MS9

Time-Periodic Delay Models of Milling Processes

During machining the regeneration of surface waviness can cause unstable self-excited vibrations known as chatter. Despite over one century of research, there remain many challenges in the avoidance of chatter because it constrains the productivity of machining operations. For the case of milling the rotating cutting tool possesses multiple teeth, which each remove material from the workpiece. The cutting force is a function of the thickness of this material, and consequently the force is also dependant on the relative vibration between the tool and the workpiece. If the dynamics of the system are linear then this leads to a delayed differential equation with linear time periodic coefficients due to the tool rotation. The stability of this system can be investigated using various techniques, such as Time Finite Element Analysis, Semi-discretisation, or a Fourier series expansion of the time-periodic terms. Recent work by the authors has focussed on the special case of variable helix tools. Here, the time delay between successive teeth varies across the axial length of the cutter. This leads to a distributed time delay that can be used to enhance the stability of the system. The present contribution will describe the challenges of modelling the stability of this system. It will be shown that the Fourier series and Fourier transform provide an elegant means of assessing stability, but that other un-modelled phenomena could be important for this configuration of milling tool.

Neil D. Sims
Department of Mechanical Engineering
University of Sheffield
n.sims@sheffield.ac.uk

Luis Urena
The University of Sheffield
ueluis1@sheffield.ac.uk

Erdem Ozturk
The University of Sheffield
Advanced Manufacturing Research Centre
e.ozturk@sheffield.ac.uk

MS9

State-Dependent Delay Effects in Drilling

In this effort, a reduced-order system of a drill string, which is a flexible structure used in oil well drilling operations, is used to study coupled axial-torsion dynamics of the system. The system model has a state-dependent delay. The different parameters that are considered include the cutting coefficient, penetration rate, and the rotation speed. The effects of the state-dependent delay on the system dynamics are examined by carrying out stability analyses, and it is discussed as to why the consideration of this state-dependent delay is important for drill-string dynamics.

Balakumar Balachandran
Dept. of Mechanical Engineering
University of Maryland
balab@umd.edu

Xie Zheng
Department of Mechanical Engineering
University of Maryland, College Park, MD 20742
xiezheng@umd.edu

MS10

Spatial and Temporal Spread of Infectious Pathogens

Infectious pathogens are as mobile as the hosts they are infecting. Understanding mobility is therefore important if one wants to understand how pathogens spread in space and time. I will present some models that have been used to address the mobility of individuals, with a focus on the use of these models in the context of epidemiology. These models consist typically of large systems of ordinary differential equations or continuous time Markov chains. I will discuss some of the mathematical challenges arising when considering such systems and show some real world applications.

Julien Arino
University of Manitoba, Canada
Julien.Arino@umanitoba.ca

MS10

Revisiting Contact and Disease Transmission Through the Lens of Fluid Dynamics

The mechanisms governing the transfer of pathogens between infected and non-infected members of a population are critical in shaping the outcome of an epidemic. This is true whether one considers human, animal or plant populations. Despite major efforts aimed at the mathematical modeling and mitigation of infectious diseases, the fundamental mechanisms of pathogen spreading for most infectious diseases remain poorly understood. Drawing upon clinical data, fluid experiments and theoretical modeling I will discuss the dynamics of transmission of various pathogens through the lens of fundamental fluid fragmentation and nonlinear dynamics.

Lydia Bourouiba
Massachusetts Institute of Technology
lbouro@MIT.EDU

MS10

Division Patterns and Dynamics of Hematopoietic Stem Cells

Mathematical modelling has long been employed to understand cellular dynamics and to supplement experimental knowledge and measurements. Mathematical techniques applied in the study of hematopoietic stem cells (HSCs) and stem cell biology include both deterministic population level models and stochastic applications, and are able to recreate and help interpret experimental labelling data. Models can advance our understanding of the homeostasis of hematopoiesis and contribute to our comprehension of the dynamics of cancers like chronic myeloid leukemia (CML), including rare presentations such as periodic CML. In this talk, I will present a delay differential equations model of HSC dynamics that incorporates the long-term, intermediate-term, and short-term HSCs, multipotent progenitors, and neutrophils to characterise the relative prevalences of symmetric self-renewal and differentiation, and asymmetric division present in the HSC populations.
Historically, the HSCs were thought to be a relatively dormant and homogeneous population, but new evidence points to heterogeneous subpopulations with variable levels of mitotic activity. By studying the ratios of each division type, this work sheds light on how HSCs constantly regenerate the blood system, and how deviations from the homeostatic control of blood cell production can induce pathological presentations like CML.

Morgan Craig
Harvard University
morgan.craig@umontreal.ca

MS10

Normal and Pathological Dynamics of Platelets in Humans

Periodic hematological diseases are dynamic diseases in which the number of one or more of the red blood cells, white blood cells, and platelets oscillate in time. While several periodic hematological diseases such as cyclic neutropenia and periodic chronic myelogenous leukemia are now well understood, the pathogenesis of cyclic thrombocytopenia (oscillating platelet numbers) remains unclear. We present a comprehensive mathematical model of platelet, megakaryocyte, and thrombopoietin dynamics in humans and use this model to investigate the etiology of cyclic thrombocytopenia. Carefully estimating model parameters from laboratory and clinical data, we then argue that a subset of parameters are involved in the genesis of cyclic thrombocytopenia based on clinical information. We provide model fits to the existing data for both platelet counts and thrombopoietin levels by changing four parameters that have physiological correlates. Our results indicate that the primary change in cyclic thrombocytopenia is an interference with, or destruction of, the thrombopoietin receptor with secondary changes in other processes, including immune-mediated destruction of platelets and megakaryocyte deficiency and failure in platelet production.

Gabriel Langlois
Brown University
gabriel_provencher_langlois@brown.edu

Morgan Craig
Harvard University
morgan.craig@umontreal.ca

Tony R. Humphries
McGill University
Mathematics and Statistics
Tony.Humphries@mcgill.ca

Michael Mackey
McGill University, Canada
michael.mackey@mcgill.ca

Joseph M. Mahaffy
San Diego State University
Dept of Mathematical Sciences
mahaffy@saturn.sdsu.edu

Jacques Belair
Département de mathématiques et de statistique
Université de Montréal
belair@crm.umontreal.ca

Thibault Moulin
Laboratoire Chrono-Environnement,
Université de Bourgogne Franche-Comté
thibault.moulin@univ-fcomte.fr

Sean Sinclair
Department of Mathematics and Statistics
McGill University
sean.sinclair@mail.mcgill.ca

Liangliang Wang
Department of Statistics and Actuarial Science
Simon Fraser University
liangliang_wang@sfu.ca

MS11

Mathematical Models for Cell Polarization and Gradient Sensing

Directed or polarized growth and the detection of chemical gradients are two fundamental cellular processes. Here we combine mathematical modeling with various experimental approaches to investigate the molecular mechanisms that underline both processes during the mating response of Saccharomyces cerevisiae (budding yeast). Our analysis reveals a novel method for gradient sensing and insight into the biochemical mechanisms that ensure the establishment of a unique polarity site.

Timothy Elston
University of North Carolina, Chapel Hill
telston@med.unc.edu

MS11

Model for Cell Polarization Based on Coupled Membrane-Bulk Diffusion

Division, differentiation and proliferation of living cells rely on mechanisms of symmetry breaking. A key element of these mechanisms is emergence of asymmetric (polar) distributions of signaling molecules, often in form of molecular clusters. Clustering may be directed by external cues, but can also occur spontaneously. Multiple positive feedback loops play a crucial role in establishing yeast polarity. We discuss a model for stationary patterns and self-sustained spatiotemporal oscillations based on passive diffusion of Rho GTPase in the interior coupled to reactions on the membrane of lower dimensionality. The coupling of the bulk and active membranes arises through both nonlinear flux boundary conditions for the bulk diffusion field and from feedback terms, depending on the local bulk concentration, to the dynamics on each membrane. The proposed model can explain behavior of Cdc42 signaling molecule in budding and fission yeast.

Alexandra Jilkine
University of Notre Dame
ajilkine@nd.edu

MS11

Partner Search Strategy and Mechanisms of Polarization During Fission Yeast Mating

Cell pairing is central for many processes, including immune defense, neuronal connection or sexual reproduction. How does a cell precisely orient towards a partner, especially when faced with multiple choices? During conditions of nitrogen starvation, the model eukaryote S. pombe (fission yeast) undergoes sexual sporulation. Because fission yeast are non-motile, contact between opposite mating types is accomplished by polarizing growth in each mating type towards the selected mate, a process known as shmooing. We used a combination of computational modeling and experiments (performed by collaborators in the group of Sophie Martin, University of Lausanne) to model the role of the exploratory Cdc42-GTP zone that appears and disappears along the cortex and stabilizes in response to secreted pheromone. We find that efficient pair formation occurs through the combination of local pheromone release, short pheromone decay length, and local pheromone sensing. This result matches experimental observations of cells lacking the predicted GTPase-activating protein for Ras, which exhibit stabilized zones at reduced pheromone levels. We propose that during mating, Cdc42 responds to a Ras activator-inhibitor dynamical system along the cell membrane, undergoing a transition from exploratory to stable localized states in response to opposite mating type pheromone.

Dimitrios Vavylonis, Bita Khalili
Lehigh University

vavylonis@lehigh.edu, bik213@lehigh.edu

MS11

A PDE-DDE Model for Cell Polarization in Fission Yeast

We consider a one-dimensional model of cell polarization in fission yeast consisting of a hybrid partial differential equationdelay differential equation system. The model describes bulk diffusion of the signaling molecule Rho GTPase Cdc42 in the cytoplasm, which is coupled to a pair of delay differential equations at the ends of the cell via boundary conditions. The latter represent the binding of Cdc42 to the cell membrane and rerelease into the cytoplasm via unbinding. The nontrivial nature of the dynamics arises from the fact that both the binding and unbinding rates at each end are taken to depend on the local membrane concentration of Cdc42. In particular, the association rate is regulated by positive feedback and the dissociation rate is regulated by delayed negative feedback. We use linear stability analysis and numerical simulations to investigate the onset of limit cycle oscillations at the end compartments for a cell of fixed length. We find that the critical time delay for the onset of oscillations via a Hopf bifurcation increases as the diffusion coefficient decreases. We then solve the diffusion equation on a growing domain under the additional assumption that the total amount of the signaling molecule increases as the cell length increases. We show that the system undergoes a transition from asymmetric to symmetric oscillations as the cell grows, consistent with experimental findings of new-end-take-off in fission yeast.

Bin Xu
University of Utah
xu@math.utah.edu

MS12

Transactive System Design and Analysis for Smart Grid Applications

As demand response is becoming increasingly important for smart grid applications, various control schemes have been developed to engage responsive loads in demand response programs in order to provide various ancillary services to the power grid. Among the existing control strategies, transactive coordination and control have attracted considerable research attentions. It uses economic or market-like constructs to manage distributed smart grid assets and is amenable to problems where self-interested users are coordinated to achieve global control objectives. Transactive control framework actually complements the conventional centralized control framework associated with direct load control. It is based on distributed control and has the significant advantages of scalability, flexibility and interoperability when applying to the large-scale systems such as power grid. On the other hand, with transactive control framework implemented at the distribution level, it will be promising to integrate demand response into the wholesale transactive operations to realize the transactive operation framework for the power system.

Jianming Lian, Karanjit Kalsi
PNNL
jianming.lian@pnnl.gov, karanjit.kalsi@pnnl.gov

MS12

A Multiobjective MPC Approach for Autonomously Driven Electric Vehicles

We present a new algorithm for model predictive control of non-linear systems with respect to multiple, conflicting objectives. The idea is to provide a possibility to change the objective in real-time, e.g. as a reaction to changes in the environment or the system state itself. The algorithm utilizes elements from various well-established concepts, namely multiobjective optimal control, economic as well as explicit model predictive control and motion planning with motion primitives. In order to realize real-time applicability, we split the computation into an online and an offline phase and we utilize symmetries in the open-loop optimal control problem to reduce the number of multiobjective optimal control problems that need to be solved in the offline phase. The results are illustrated using the example of an electric vehicle where the longitudinal dynamics are controlled with respect to the concurrent objectives arrival time and energy consumption.

Sebastian Peitz
University of Paderborn
speitz@math.uni-paderborn.de

Kai Schäfer
Paderborn University
kaisch@math.uni-paderborn.de

Sina Ober-Blöbaum
Oxford University
sina.ober-blobaum@eng.ox.ac.uk

Julian Eckstein, Ulrich Köhler
Hella KGaA Hueck & Co.
julian.eckstein@hella.com, ulrich.koehler@hella.com

Michael Dellnitz
University of Paderborn, Germany
dellnitz@uni-paderborn.de

MS12

Computational Methods for Dynamic Constrained Optimization

An important class of problems in optimal control design is defined with constraints that are not static but described by continuous dynamics of a nonlinear system. Such constraints are infinite dimensional. To solve a problem with such constraints, one needs to apply a discretization scheme to get a finite dimensional approximation. The dimensionality of such approximate problem can become quite large and the problem is often computationally challenging to handle. In this talk we present a computational approach for dynamic constrained optimization that circumvents the high dimensionality by using a reduced-space optimization approach together with state-of-the-art ODE/DAE integrators and adjoint-based optimization gradient evaluation. We will demonstrate this approach in applications to power transmission planning and operation, where, for example, computing dynamic security constrained optimal power flow is essential for deciding the appropriate control actions. We believe our approach will enable a number of optimal power flow computations currently run off-line to run in real time and, hence, provide grid operators far more flexibility in decision making. Added flexibility will help incorporate in the power grid more renewables such as solar and wind, whose behavior is less predictable than the behavior of traditional energy resources. We will discuss how to manage complexity of these computations and make it easily accessible to domain experts in the industry.

Slaven Peles
Lawrence Livermore Natinoal Laboratory
peles2@llnl.gov

Cosmin G. Petra
Lawrence Livermore National
Center for Advanced Scientific Computing
petra1@llnl.gov

MS12

Optimal Sensor Placement Using Graph Metrics

The problem of assigning limited resources to nodes on a graph arises either directly or indirectly in a wide variety of applications like influence maximization in social networks. Such problems are typically formulated as variants of the k-median problem for which solutions are obtained using approximation algorithms. In this work, we propose an alternative approach for identifying nodes in a graph for assignment of resources (such as sensors and advertisements etc.) The approach relies on computing the minimum of a coverage metric that is defined in terms of the eigenvectors of the associated graph Laplacian. This solution is shown to serve as an alternative for the solution to the k-median problem. We then exploit this approach to optimally place heterogeneous sensors over large non-convex regions. This optimal sensor placement approach finds solutions that are computationally efficient with high coverage.

Tuhin Sahai
United Technologies
sahait@utrc.utc.com

George Mathew
iRhythm Technologies
george_cet@yahoo.com

MS13

Rigorous Integration Forward in Time of Pdes Using Chebyshev Basis

We present a rigorous numerical procedure for integration forward in time of one-dimensional dissipative PDEs with periodic boundary conditions using the Chebyshev's series expansion in time of the solution. Our method is a Newton operator like approach, and we also make use of the radii polynomial method. Central to our approach is a proof of stability of a norm for inverses of linear operator with respect to the Galerkin approximation dimension. Using this result we are able to apply the contraction principle in infinite dimensional Banach space, for a sufficiently small time-step.

Jacek Cyranka
Rutgers University
jcyranka@gmail.com

Jan-Philippe Lessard
Université Laval
jean-philippe.lessard@mat.ulaval.ca

MS13

Validated Computation of Transport Barriers in Unsteady Flows

Transport barriers are time-varying generalizations of invariant manifolds which separate the phase space into distinct regions between which few, if any, orbits pass. In contrast to the separatrices of autonomous systems, transport barriers are not typically invariant sets which has made their characterization notoriously difficult. Recently, the study of Lagrangian coherent structures (LCS) and almost-invariant sets have led to an improved understanding of transport in these systems. Specifically, these approaches have yielded reliable diagnostic tools such as the finite-time Lyapunov exponent (FTLE), geodesic deviation, as well as estimates of diffusion and filamentation. In this work we combine numerical diagnostics with a-posteriori analysis and validated numerics to obtain computer assisted proofs of existence for some LCS/almost-invariant sets. In particular, we introduce a method to compute rigorous enclosures of FTLE and geodesic deviation for codimension-one surfaces. As a by-product, we also obtain mathematically rigorous bounds on the location as well as interval of existence for transport barriers. This information is useful not only for characterization but also for benchmarking existing diagnostics. The utility of our methods are illustrated in examples.

Shane D. Kepley
Florida Atlantic University
skepley@fau.edu

Jason D. Mireles James
Rutgers University
jmirelesjames@fau.edu

MS13

Nontrivial Dynamics in the Forced Navier-Stokes Equations: A Computer-Assisted Proof

In this talk, we introduce a rigorous numerical method to prove existence of periodic orbits in the forced Navier-Stokes (NS) equations. After reformulating the NS equations in their vorticity formulation, we expand the periodic orbits using Fourier series both in space and in time and solve for the Fourier coefficients in a Banach algebra of geometrically decaying sequences. The proof of existence follows by applying a Newton-Kantorovich type argument (the radii polynomial approach) close to a numerical approximation. We use this approach to prove existence of two-dimensional periodic orbits in the NS equations.

Jean-Philippe Lessard
Université Laval
jean-philippe.lessard@mat.ulaval.ca

Jan Bouwe Van Den Berg
VU University Amsterdam
janbouwe.vanden.berg@vu.nl

Maxime Breden
ENS Paris-Saclay & Université Laval
maxime.breden@ens-cachan.fr

Lennaert van Veen
UOIT
lennaert.vanveen@uoit.ca

MS13

Recent Progress on Computational Theorems in

Dynamics

In nonlinear analysis we often simulate dynamics of a system of ODEs on a computer, or calculate a numerical solution to a partial differential equation. This gives very detailed, stimulating information. However, it would be even better if we can be sure that what we see on the screen genuinely represents a solution of the problem. In particular, rigorous validation of the computations would allow such objects to be used as ingredients of (forcing) theorems. The past decade has seen enormous advances in the development of computer assisted proofs in dynamics. Attention is now turning to *infinite* dimensional nonlinear dynamics generated by PDEs, integral equations, delay equations, and infinite dimensional maps. In this talk we will review recent developments and set the stage for the other talks in this minisymposium. We will discuss existence, continuation and bifurcations of periodic orbits in systems of ODEs, delay equations as well as PDEs (including spatio-temporal periodic patterns). Other examples include the rigorous computation of invariant manifolds and connecting orbits for ODEs, PDEs and delay equations.

Jan Bouwe Van Den Berg
VU University Amsterdam
Department of Mathematics
janbouwe@few.vu.nl

MS14

Role of Neuron-Glia Interaction in Epileptogenesis

Neuronal activity is strongly reduced in chronically isolated cortex. In response to prolonged synaptic inactivity astrocytes release tumor necrosis factor alpha (TNFa), which diffuses and binds to its dedicated receptors on the neurons causing a reduction in the number of postsynaptic GABA and an increase in the number of AMPA and NMDA receptors. This process called homeostatic plasticity (HSP) upregulates depolarizing influences (such as excitatory intrinsic and synaptic conductances) and downregulates hyperpolarizing ones (such as inhibitory conductances). We propose and test a hypothesis that homeostatic plasticity, which normally maintains a moderate level of activity in the cortex, fail to control normal excitability in heterogeneous networks, where there are subpopulations of neurons with severely different levels of activity conditions found in traumatized cortex. Thus, according to our hypothesis, trauma induced deafferentation leads to an acute decrease of neuronal activity in affected areas, triggering upregulation of neuronal excitability that in conditions of severe deafferentation may lead to instabilities and development of epilepsy.

Maxim Bazhenov
Department of Cell Biology and Neuroscience
University of California, Riverside
mbazhenov@ucsd.edu

MS14

Minimal Modeling of GPCR-Mediated Calcium Signaling

Calcium signaling mediated by Gprotein-coupled receptors (GPCRs) is deployed by many different cells to carry and propagate information from the extracellular environment to targets in their interior. In healthy vs. pathological cellular states, GPCR-mediated intracellular calcium dynamics may vary largely, showing disease-specific spatial-temporal features. It is challenging however to associate such different features with individual reactions of the underlying complex biochemical signaling networks, due to the large dimension of the system and its inherent nonlinearities. How can we reduce dimensions for the sake of mathematical tractability yet retaining essential biophysical features? What are the criteria for the choice of these features? To address these questions, I will focus on metabolic modeling of the calcium-triggering molecule inositol 1,4,5-trisphosphate (IP_3) in astrocytes the predominant cortical glial cell type. By simple analytic arguments, I will illustrate how the interplay between different time scales of IP_3 production and degradation, could account for a large spectrum of healthy and pathological astrocytic calcium signaling, pinpointing to specific molecular mechanisms. The possibility to clearly identify these mechanisms direct follows from the implemented system reduction procedure, accounting for different steps of propagation of perturbations, from activated GPCRs on the extracellular side of astrocytes, to targets in their interior.

Maurizio De Pittà
University of Chicago
maurizio.depitta@gmail.com

MS14

Mathematical Investigation of Ion Dynamics in Astrocytes and the Extracellular Space

Astrocytes are glial cells in the brain that each wrap around thousands of synapses. Neurotransmitters released by neurons can activate receptors on astrocytes, leading to the release of IP3, and initiating calcium transients in astrocytes. It is believed that these transients allow astrocytes to communicate with nearby neurons, but the mechanisms are still being investigated. One proposed pathway is through the sodium-calcium exchanger activated by the increase in astrocyte cytosolic calcium. The exchanger activity affects the sodium-potassium pump, enabling astrocytes to regulate extracellular ion concentrations, and thus the neuronal excitability. We study viability of such communication pathway. Using experimental data collected by our collaborators, we first study the calcium responses evoked by short puffs of ATP. We develop an open-cell, single compartment minimal ODE model that captures the experimentally observed diversity of calcium transients. By varying the strength of calcium channels, we manipulate the underlying bifurcation structure of the ODE system, thus examining the specific roles of individual calcium fluxes and making testable predictions. Building off of this understanding, we then introduce sodium and potassium fluxes. Altering the strengths of these new fluxes, we explore the impacts calcium transients in astrocytes can have on extracellular ionic concentrations and the firing patterns of neighboring neurons in healthy and pathological states.

Gregory A. Handy
University of Utah Mathematics Department
handy@math.utah.edu

Marsa Taheri
University of Utah
Department of Bioengineering
marsa.taheri@utah.edu

John A. White
Biomedical Engineering
Boston University
jwhite@bu.edu

Alla Borisyuk
University of Utah
Dept of Mathematics
borisyuk@math.utah.edu

MS14

The Role of Astrocytic Glutamate Uptake in Neuronal Ion Homeostasis: A Case Study of Spreading Depolarization

Simultaneous changes in ion concentrations, glutamate, and cell volume together with exchange of matter between cell network and vasculature are ubiquitous in numerous brain pathologies. A complete understanding of pathological conditions as well as normal brain function, therefore, hinges on elucidating the pathways involved in these mostly interdependent variations. In this paper, we combine the Hodgkin–Huxley type spiking dynamics, dynamic ion concentrations and glutamate homeostasis, neuronal and astroglial volume changes, and ion exchange with vasculature into a comprehensive model to elucidate the role of glutamate uptake in the dynamics of spreading depolarization (SD) - the electrophysiological event underlying numerous pathologies including migraine, ischemic stroke, aneurysmal subarachnoid hemorrhage, and trauma. Our results demonstrate that glutamate signaling is the intrinsic mechanism of SD, and that impaired glutamate uptake leads to recovery failure of neurons from SD. We confirm predictions from our model experimentally by showing that inhibiting astrocytic glutamate uptake using TFB-TBOA nearly quadruples the duration of SD in cortical slices from juvenile rats. The model equations are either derived from a combination of first physical principles of electroneutrality, osmosis, and conservation of particles and known physiological facts. Accordingly, we claim that our model is broadly applicable to other brain pathologies and normal brain function.

Ghanim Ullah, Niklas Hubel
University of South Florida
gullah@usf.edu, niklas.huebel@gmail.com

Jokubas Ziburkus
University of Houston
jziburku@central.uh.edu

MS15

Eigenvector Localization in Complex Networks

Analysis of eigenvector localization properties are important due to its various applications including networks centrality, spectral partitioning, and disease spreading phenomena in complex networks. We evolve an initially random network with an edge rewiring technique using inverse participation ratio as a fitness function to obtain a network, which has the most localized principal eigenvector, and analyze the structural properties of the optimized networks. It turns out that in the optimized network there exists a set of edges that are crucial for the localization, rewiring only one of them leads to a complete delocalization of the principal eigenvector. We analytically derive the condition for changes in the IPR values for the edge rewiring. The work has potential applications in designing technological networks such as computer virus propagation network, transport network, and systems requiring vibration confinement such as spring-mass-damper systems, and piezoelectric networks.

Sarika Jalan
Complex Systems Lab
Indian Institute of Technology Indore
sarikajalan9@gmail.com

MS15

Inferring Network Topology from Observational Data: Potentials and Pitfalls

We analyse climate dynamics from a complex network approach. This leads to an inverse problem: Is there a backbone-like structure underlying the climate system? For this we propose a method to reconstruct and analyze a complex network from data generated by a spatio-temporal dynamical system. We use different classic techniques for this reconstruction and find various pitfalls. Therefore, three other procedures are proposed based on recurrence, on conditional expectations and on a macroscopic approach. These approaches enable us to uncover relations to global circulation patterns in oceans and atmosphere, in particular teleconnections. Potentials of these techniques are demonstrated.

Juergen Kurths
Humboldt Univ,Germany, Potsdam Institute for Climate Impact
Research, Germany, and Aberdeen University, UK
juergen.kurths@pik-potsdam.de

MS15

Experimental Observation of Spiral Wave Chimera in a Very Large Network of Chemical Oscillators

I will present a versatile experimental setup based on optically coupled catalytic micro-particles, that allows for the experimental study of synchronization patterns in very large networks of relaxation oscillators under well-controlled laboratory conditions. In particular I will show our experimental observation of the spiral wave chimera, predicted by Kuramoto in 2003. This pattern features a wave rotating around a spatially extended core that consists of phase-randomized oscillators. We study its existence depending on coupling parameters and observe a transition to incoherence via core growth and splitting. The spiral wave chimera is likely to play a role in cardiac and cortical cell ensembles, as well as in cilia carpets.

Jan Totz
Institut für Theoretische Physik
Technische Universität Berlin
janjan2.71828@googlemail.com

Kenneth Showalter
West Virginia University
Department of Chemistry
kshowalt@wvu.edu

Harald Engel
Institut für Theoretische Physik, Technische Universität Ber
10623 Berlin, Germany
h.engel@physik.tu-berlin.de

MS15

Partial Cascades on One-Dimensional Geographic Networks

We examine the question of cascades on networks where the connections between nodes are heavily dependent on some underlying spatial geography. Our focus is on the Centola-Macy model of cascade dynamics, where nodes will activate if they have a sufficient number (not a sufficient proportion) of active neighbors. We consider cases where the connections are short enough that the cascade can be viewed as a wave front propagation and there is no activation of new clusters. Of particular interest is the possibility of the termination of the cascade and the probability distribution of final cascade sizes. We model the number of agents that activate on each time step as a Markov chain and estimate the extinction probability as a function of time. We derive a model to predict the final cascade size distribution for one-dimensional networks with uniformly distributed nodes.

Yosef M. Treitman
Rensselaer Polytechnic Institute
treitmaniac@gmail.com

MS16

Noise-Induced Rare Events in Population Dynamics: the Role of Spatial Degrees of Freedom

We study the influence of the network topology on the statistics of interest including rare events of interacting particle systems on complex graphs. As an example, we investigate the metastability and fixation properties of a set of evolutionary processes. In the framework of evolutionary game theory, where the fitness and selection are frequency dependent and vary with the population composition, we analyze the dynamics of snowdrift games (characterized by a metastable coexistence state) on scale-free networks. Using an effective diffusion theory in the weak selection limit, we demonstrate how the scale-free structure affects the systems metastable state and leads to anomalous fixation compared to the non-spatial well-mixed case. In particular, we analytically and numerically show that the probability and mean time to fixation are characterized by stretched-exponential behaviors with exponents depending on the networks degree distribution.

Michael Assaf
Racah Institute of Physics
Hebrew University of Jerusalem
michael.assaf@mail.huji.ac.il

MS16

How Do Cells Extract Information About the Direction of Signaling Molecule Gradients to Make Decisions?

Nearly all eukaryotic cells organize macromolecules by positioning them in specific locations relative to an external signal. This organizing process is known as polarization and is often directed along a gradient of an external signaling molecule. Like many cellular processes, polarization decisions are made using a relatively small number of molecules and are thus susceptible to internal and external fluctuations during signal transduction. How cells manage to transform a noisy external signal into accurate directional sensing is an open question in cellular biology. Here, I present results showing that spatial structure in the signaling molecule distribution plays a key role in extracting directional information. Our simulation data show that an architecture combining bistability with spatial positive feedback permits the cell to both accurately detect and internally amplify an external gradient. We observe strong polarization in all individual cells, but in a distribution of directions centered on the gradient. Polarization accuracy in our study was strongly dependent upon a spatial positive feedback term. Simulation data support a role for cytoskeletal remodeling in this spatial feedback, constituting a cellular memory regarding directions. Finally, we show that additional feedback links providing information about the gradient to multiple levels in the pathway can help the cell to refine initial inaccuracy in the polarization direction.

Elijah Roberts
Department of Biophysics
Johns Hopkins University
eroberts@jhu.edu

MS16

Making Rare Events Happen: Prediction and Control of Extinction and Switching in Heterogeneous Networks

We consider epidemic extinction as rare events in finite networks with broad variation in local connectivity. Given random networks with a given degree distribution, we are able to predict the most probable, or optimal, paths to extinction in various configurations, including truncated power-laws. We find that paths for heterogeneous networks follow a limiting form in which infection first decreases in low-degree nodes, which triggers a rapid extinction in high-degree nodes, and finishes with a residual low-degree extinction. The usefulness of our approach is further demonstrated through optimal control strategies that leverage the dependence of finite-size fluctuations on network topology. Interestingly, we find that the optimal control is a mix of treating both high and low-degree nodes based on theoretical predictions, in contrast to methods that ignore dynamical fluctuations. This research is supported by the Office of Naval Research.

Ira B. Schwartz
Naval Research Laboratory
ira.schwartz@nrl.navy.mil

Jason Hindes
US Naval Research Laboratory
US Naval Research Laboratory
jason.hindes.ctr@nrl.navy.mil

Brandon Lindley
Ralph Wagner Associates
brandon.s.lindley@gmail.com

Leah Shaw
College of William and Mary
Dept. of Applied Science
lbshaw@wm.edu

MS16

Epidemic Extinction in Adaptive Networks with Avoidance Rewiring

During epidemic spread on a network, individual nodes may adapt their connections to reduce their chance of infection. A commonly modeled form of adaptation is avoidance rewiring, where a noninfected node rewires a link away from an infected node, instead connecting to another noninfected node. In a susceptible-infected-susceptible (SIS) disease model, small rewiring results in a single stable steady state, but larger rewiring leads to a backward bifurcation and bistability between an endemic state and a disease free state. We compare stochastic extinction in both the small and larger rewiring cases. Applying large deviation theory on an adaptive network, we predict extinction times and find the most probable path to extinction. The analysis is compared with stochastic simulations of the network.

Leah Shaw
College of William and Mary
lbshaw@wm.edu

Jason Hindes
US Naval Research Laboratory
US Naval Research Laboratory
jason.hindes.ctr@nrl.navy.mil

Ira B. Schwartz
Naval Research Laboratory
ira.schwartz@nrl.navy.mil

MS17

Chaotic Sequences for Synchronization and Communication

A major impediment to coherent chaotic communications is the difficulty of synchronizing the receiver to the transmitter. In this work, a set of dictionary sequences is created from a chaotic map. The dictionary sequences may be concatenated in a way that minimizes the discontinuity between the end of 1 sequence and the beginning of the next sequence. The receiver has a copy of these dictionary sequences, so it uses a correlation detector followed by a Viterbi decoder to estimate the transmitted sequences, allowing the receiver to be synchronized to the transmitter. Once synchronization is achieved, information can be transmitted by multiplying the transmitted signal by + or 1 to encode a binary 1 or 0. The binary values are detected in the receiver by cross correlation. The bit rate can be increased by using the multiple components of the chaotic map to create multiple orthogonal signals. The encoding technique is equivalent of binary phase shift keying, and gives the same bit error rate.

Thomas L. Carroll
Naval Reseach Laboratory
thomas.carroll@nrl.navy.mil

MS17

Chaos Theory in Communications: Applications and Challenges

Since the early 1990s, a large number of chaos-based communication systems have been proposed exploiting the properties of chaotic waveforms. The motivation lies in the significant advantages provided by this class of nonlinear signals. For this aim, many communication schemes and applications have been specially designed for chaos-based communication systems where energy, data rate, and synchronization awareness are considered in most designs. Recently, the major focus, however, has been given to the non-coherent chaos-based systems to benefit from the advantages of chaotic signals and non coherent detection and to avoid the use of chaotic synchronization, which suffers from weak performance in the presence of additive noise. This talk presents a comprehensive survey of the widely used wireless radio frequency chaos-based communication systems. First, it outlines the challenges of chaos implementations and synchronization methods, followed by comprehensive literature review and analysis of chaos-based coherent techniques and their applications. In the second part of the talk, we offer a taxonomy of the current literature by focusing on non-coherent detection methods. Finally, several concluding remarks are discussed.

Georges Kaddoum
Département de génie électrique
École de technologie supérieure
georges.kaddoum@etsmtl.ca

MS17

Chaotic OFDM System for Secure Multi-User Communications

Chaotic modulation schemes, Orthogonal Frequency Division Multiplexing(OFDM) and Interference Alignment(IA) are combined in order to obtain an inversely proportional relationship between throughput and detectability of transmit signals in multi user environment. A mixture of chaotic modulation schemes is used to generate chaotically modulated symbols for each sub-carrier of the OFDM transmitter. This technique can eliminate the physical layer security concerns in conventional OFDM systems. Throughput degradation due to interference can be minimized using IA. In particularly, IA can be applied independently inside disjoint subsets of subcarriers [J. Reitterer and M. Rupp, Interference alignment in UMTS Long Term Evolution, 19th European Signal Processing Conference, 2011]. At the receiver side, interference suppression is performed on disjoint subsets of sub-carriers. Then, a mixture of correlators and mean value functions are implemented to demodulate chaotic signals [H. Leung, S. Shanmugam, N. Xie, S. Wang, "An ergodic approach for chaotic signal estimation at low SNR with application to ultra-wide-band communication," IEEE Trans. on Information on Signal Processing, 2006]. The statistical random tests, time domain randomness tests and frequency domain randomness tests are used to confirm the improvements in physical layer security. The improvements in throughput is investigated to ensure the inversely proportional relationship between detectability and throughput.

Henry Leung, Chatura Seneviratne
University of Calgary
Department of Electrical and Computer Engineering
leungh@ucalgary.ca, ckwickre@ucalgary.ca

MS17

Wireless Communication with Chaos

The constraints of a wireless physical media, such as multipath propagation and complex ambient noises, prevent information from being communicated at low bit error rate. Surprisingly, it has only recently been shown that, from a theoretical perspective, chaotic signals are optimal for coherent communication. It maximises the receiver signal-to-noise performance, consequently minimizing the bit error rate. This talk demonstrates numerically and experimentally that chaotic systems can in fact be used to create a reliable and efficient wireless communication system. We also show that the chaotic signals provide a easy way to decrease the inter-symbol interference caused by multipath. We propose an impulsive control method to generate chaotic wave signals that encode arbitrary binary information signals, and a sub-optimal threshold to detect information bits. The experimental validation is conducted by inputting the signals generated by an electronic transmitting circuit to an electronic circuit that emulates a wireless channel, where the signals travel along three different paths. The output signal is decoded by an electronic receiver, after passing through a match filter. The simulation results also are given to show that the proposed sub-optimal threshold can achieve very competitive performance.

Hai-Peng Ren
Xi'an Univeristy of Technology
P R China
renhaipeng@xaut.edu.cn

Chao Bai, Jun-Liang Yao
Xi'an University of Technology
moonanimal@sina.com, yaojunliang@xaut.edu.cn

Murilo Baptista
University of Aberdeen
murilo.baptista@abdn.ac.uk

Celso Grebogi
King's College
University of Aberdeen
grebogi@abdn.ac.uk

MS18
Models of Value-Sensitive Decision Making

Decision making is crucially important at all levels of biological complexity. Two-alternative choice tasks, for example, are widely studied in terms of accumulation of relative evidence. Related models are known to implement a speed-accuracy tradeoff [Bogacz et al., Psychol. Rev. 113: 700 (2006)]. However, based on findings in house-hunting honeybees [Pais et al., PLOS ONE 8: e73216 (2013)], and recent results obtained from behavioral data [Teodorescu et al., Psychon. Bull. Rev. 23: 22 (2016)], we follow an approach that describes value-based decisions, which should be related to a speed-value tradeoff rather than a speed-accuracy tradeoff [Pirrone et al., Front. Neurosci. 8: 1 (2014)]. Here, we compare the performance of different nonlinear neuro-models of decision making that differ in the way the inhibition mechanism is implemented, i.e. feed-forward, mutual and interneuronal inhibition. Assigning quality values to available options we are able to study the dynamics of the decision-maker depending on the quality of options and the balance between positive and negative feedback. Considering two options, which are of equal quality to the decision-maker, we apply the interneuronal inhibition model to a hypothetical animal making foraging decisions. As a result, we find that in an ongoing decision-making process oscillatory behavior may improve the performance of the animal. Our results motivate an integrated functional and mechanistic study of animal decision-making.

Thomas Bose, Andreagiovanni Reina, James A R Marshall
Department of Computer Science
University of Sheffield, Regent Court, Sheffield, S1 4DP, UK
t.bose@sheffield.ac.uk, a.reina@sheffield.ac.uk, james.marshall@sheffield.ac.uk

MS18
Evidence Accumulation in Dynamic Environments

To make decisions a constantly changing world, organisms must account for environmental volatility and appropriately discount old information when making decisions based on such accumulated evidence. We introduce probabilistic inference models of decision making, and derive an ideal observer model for inferring the present state of the environment along with its rate of change. Moment closure then allows us to obtain a low-dimensional system that performs comparable inference. These computations can be implemented by a neural network model whose connections are updated according to an activity-dependent plasticity rule. Our work therefore builds a bridge between statistical decision making in volatile environments and stochastic nonlinear dynamics of neural systems.

Zachary P. Kilpatrick
Department of Applied Mathematics
526 UCB, University of Colorado, Boulder, CO, 80309
USA
zpkilpat@colorado.edu

Adrian Radillo
University of Houston
adrian@math.uh.edu

Kresimir Josic
University of Houston
Department of Mathematics
josic@math.uh.edu

Alan Veliz-Cuba
Department of Mathematics
University of Dayton
avelizcuba1@udayton.edu

MS18
Collective Behavior and Individual Variability: From Personalities to Heterospecific Interactions

Interactions between groups and sub-groups - be they strains or species have been reported in many cases across many taxae. We here focus on interactions that are either quantitatively or qualitatively different reflecting inter-individual variability within a group or heterospecific communication. We first propose a simple model of aggregation based on earlier experiments accounting for the presence of personalities inside a group and discuss the differences in the subsequent collective behaviours as compared to a group composed by clones. We subsequently consider the case of interactions between two Physarum polycephalum individuals of the same or different strain and determine their role in their decision-making patterns. Finally, a generic model accounting for both conspecific and heterospecific interactions is outlined predicting different collective behaviours without any change of individuals algorithm as some key generic parameters such as the carrying capacity, the number of individuals involved and the strength of inter-attraction between sub-groups are varied. A key result is the possibility for sub-groups to segregate between patches and for transition between different patterns, even in absence of active agonistic behaviour.

Stamatios C. Nicolis
Unit of Social Ecology
Université Libre de Bruxelles, 1050 Bruxelles, Belgium
snicolis@ulb.ac.be

MS18
Excitability and Feedback in Regulation of Foraging Harvester Ants

Harvester ant colonies regulate the rate at which foragers leave the nest based on brief antennal interactions between incoming food-bearing foragers and potential foragers in the nest entrance chamber. Despite such limited interactions, ant colonies exhibit steady-state foraging rates that are robust to perturbation and adaptive to changes in temperature and humidity. To examine the underlying feedback mechanisms of foraging regulation, we have adapted a low-dimensional nonlinear model of neuronal excitability using the analogy between a spiking neuron and a foraging ant. Our model closes the loop around the dynamics inside the nest, which maps incoming foragers to outgoing foragers, with the dynamics outside the nest, which maps outgoing foragers to incoming foragers. Inside the nest we use a leaky integrator to model accumulation of evidence from interactions and excitability dynamics to model the decision of potential foragers to go out and forage. Outside the nest, we use a time delay distribution to model foraging. Closing the loop provides a mechanism for stability of the steady-state incoming and outgoing rates. To explain adaptation of foraging rates to changes in temperature and humidity, we propose another feedback mechanism that manages volatility in the excitability dynamics. With a small number of parameters, our model qualitatively captures a range of behaviors observed in harvester ants, and presents opportunities for generalization to other contexts.

Renato Pagliara
Mechanical and Aerospace Engineering
Princeton University, Princeton, NJ USA
rvasquez@princeton.edu

Deborah M. Gordon
Stanford University
dmgordon@stanford.edu

Naomi E. Leonard
Princeton University
naomi@princeton.edu

MS19

A Model for Nonlinear Acoustic Waves in a Nonuniform Lattice of Helmholtz Resonators

We are interested in the dynamics of nonlinear solitary acoustic waves in lattices. The main feature of these waves is that they propagate without change of shape and with a velocity depending of their amplitude. To study the propagation of high amplitude acoustic pulses in a 1D waveguide connected to a lattice of Helmholtz resonators, an homogenized model has been proposed by Sugimoto (J. Fluid. Mech., **244** (1992)). This model takes into account both the nonlinear wave propagation and various mechanisms of dissipation. We have already developed a numerical modeling of this model and we have successfully compared simulations with experimental data. In Sugimoto's model, all the resonators are the same. The drawback of this approach is that the reflection of an incident wave by a defect cannot be considered. To remedy this limitation, we propose an extension of the model, predicting two-way propagation across variable resonators. Thanks to a discrete description of the resonators, the new model takes into account two important features: resonators of different strengths and back-scattering effects. Moreover, we reformulate the viscothermal losses, which leads to a formulation suitable for an energy balance. Comparisons with experimental data show that a closer agreement is obtained than with the original Sugimoto's model. Numerical experiments are also proposed to highlight the effect of defects and of disorder.

Jean-François Mercier
Applied Mathematics Department
ENSTA ParisTech
jean-francois.mercier@ensta-paristech.fr

Bruno Lombard
LMA
lombard@lma.cnrs-mrs.fr

MS19

Symmetry-Induced Dynamic Localization in Lattice Structures

The existence of internal symmetry in lattice structures may give rise to stationary compact solutions, even in the absence of disorder and nonlinearity. These compact solutions are related to the existence of flat dispersion curves (bands). Nonlinearity can be a destabilizing factor for such compactons. This can be illustrated even by a simple one-site model, in which the compacton corresponds to a single hidden antisymmetric mode. This antisymmetric mode can lose its stability through parametric resonance, when accounting for nonlinear interactions. The phenomenon is examined for a chain of linearly connected massless boxes containing two masses each, coupled to the box by cubic internal interaction forces. Linear stability of the compact mode is performed rigorously for a single element by Hills method, revealing a finite width instability tongue in the parameter plane. Numerical integration for a closed chain of several boxes confirms the emergence of either a stable static compacton solution or dynamic delocalization, depending on the parameters, in correspondence with the single element stability map. In addition, a chain with internal configurational symmetry and vibro-impact on-site potentials is investigated. Rigorous stability analysis is performed for an asymptotically long chain using the notion of the saltation matrix and existence of finite stability zones of a compacton solution in the nonlinear chain is revealed.

Nathan Perchikov
Technion - Israel Institute of Technology
perchico@gmail.com

Oleg Gendelman
Technion Israel Institute of Technology
ovgend@tx.technion.ac.il

MS19

Strongly Nonlinear Acoustic Metamaterials with Passive Self-Tuning and Wave Redirection Properties

We present analytical and numerical results concerning passive nonlinear targeted energy transfer TET leading to wave redirection in networks of weakly coupled granular media. In particular, we consider two weakly coupled uncompressed granular chains of semi-infinite extent, composed of perfectly elastic spherical beads with Hertzian interactions, mounted on linear elastic foundations. One of the chains is regarded as the "excited" chain, and the other is designated as the "absorbing" chain. Both chains are initially at rest and a stratification of the coupling between the two chains is introduced. Under both impulsive and harmonic excitations of the excited chain we study the nonlinear dynamical mechanism for TET in this granular network, and identify it as a transient resonance capture.

This is manifested as a macro-scale analog of the Landau-Zener tunneling quantum effect in space. The TET mechanism provides an efficient way for wave redirection in the network, whereby breathers originally initiated in the excited chain are eventually redirected to the absorbing chain only. Numerical simulations fully validate the theoretical analysis and results.

Mohammed A. Hasan
University of California, San Diego
mdhasan@eng.ucsd.edu

Yuli Starosvetsky
Technion, Israel Institute of Technology
staryuli@tx.technion.ac.il

Leonid Manevitch
Semenov Institute of Chemical Physics
Russian Academy of Sciences
manevitchleonid3@gmail.com

Alexander Vakakis
University of Illinois
avakakis@illinois.edu

MS19

Traveling Waves in Nonlinear Metamaterials: Granular Chains and Beyond

In this talk we will present some recent progress motivated by granular crystals and related applications. We will examine traveling waves in prototypical such chains and subsequently generalize consideration to FPU type lattices of different types. We will revisit and establish a criterion for the stability of traveling waves and analyze their spectra. We will connect such traveling waves to discrete breathers and connect the criterion to one for the stability of discrete breathers. We will also explore two complementary aspects for examining the spectra of traveling waves, namely that of a steady state of a co-traveling frame which leads to an advance-delay equation, and that of a periodic orbit modulo shifts that gives rise to a suitable Floquet multiplier problem. In addition to the theoretical analysis and connections, a number of computational examples will be presented and wherever possible discussion of relevant experiments will be highlighted.

Haitao Xu
University of Minnesota
pocketxumk3t@gmail.com

Panayotis Kevrekidis
University of Massachusetts
kevrekid@math.umass.edu

MS20

Computation of the Koopman Spectrum in Complex Flows

Koopman operator theory is a powerful framework for study of high-dimensional systems including fluid flows. In particular, the eigenvalues and eigenfunctions of the Koopman operator, if existent, play a central a role in study of such systems. For example, Koopman modes, which are projection of observables onto Koopman eigenfunctions, describe the periodically evolving spatial structures in the flow, and they have become a standard tool for analysis and low-dimensional modeling of fluid flows. The spectral properties of the Koopman operator are often computed using a class of algorithms known as Dynamic Mode Decomposition (DMD), however, there has been no general theorems on convergence of these algorithms. In this talk, we present the proof of convergence for some general classes of dynamical systems and discuss some examples from computational fluid dynamics.

Hassan Arbabi
University of California, Santa Barbara
arbabi@umail.ucsb.edu

Igor Mezic
UCSB
mezic@engr.ucsb.edu

MS20

The Computation of Invariant Manifolds for Partial Differential Equations by Set Oriented Numerics

In this talk we present a novel numerical framework for the computation of finite dimensional invariant manifolds for infinite dimensional dynamical systems. With this framework we extend classical *set oriented* numerical schemes (for the computation of invariant manifolds in finite dimensions) to the infinite dimensional context. The underlying idea is to utilize appropriate *embedding techniques* for the globalization of these manifolds in a certain finite dimensional space. Finally, we illustrate our approach by the approximation of invariant manifolds in the context of partial differential equations.

Michael Dellnitz
University of Paderborn, Germany
dellnitz@uni-paderborn.de

Adrian Ziessler
Paderborn University
ziessler@math.upb.de

MS20

Fast Computation of Coherent Sets

Finite-time coherent sets are regions in the domain of some flow that minimally mix with the rest of the domain and roughly keep their geometric shape over some finite period of time, while the flow around them is more turbulent. Prominent examples in fluid flows are ocean eddies or atmospheric vortices. Techniques for the detection and computation of coherent sets are available which are based on spectral properties of appropriately defined transfer and Laplacian operators. We develop efficient numerical methods for the discretization of the associated eigenproblems, enabling a fast and accurate extraction of finite-time coherent sets, even for scattered and possibly sparse trajectory data. This is joint work with A. Denner (TUM), G. Froyland (UNSW) and D. Karrasch (TUM), cf. the talk by G. Froyland in "Koopman Operator Techniques in Dynamical Systems: Theory - Part II of II".

Oliver Junge
Center for Mathematics
Technische Universität München, Germany
oj@tum.de

MS20

Quantifying the Influence of Lateral Boundaries on

Turbulent Transport

Turbulent flows almost by definition mix efficiently: any initial patch of marked fluid will rapidly smear out and be intermingled with other fluid by the action of the flow. But this turbulent transport is also well known to be influenced, at least in finite time, by the presence of coherent structures that may either locally enhance or suppress mixing. Such structures may be pinned to features at boundaries, potentially inducing long-time effects on the mixing structure of the flow. We study such effects in a quasi-two-dimensional laboratory turbulent flow in the presence of canonical lateral boundary features, and use transfer operators to quantity the effects of these boundaries on the mixing in the flow.

Nicholas T. Ouellette
Yale University
Department of Mechanical Engineering and Materials Science
nto@stanford.edu

MS21

A Multiplex View of PageRank Through Biplex Markov Chains

PageRank is the basic ingredient of the (probably) most famous web searcher (Google), but it also has many applications to different real-life problems, ranging from biological systems to cibersecurity. In this talk, a multiplex view of the classic PageRank is presented including some analytical relations between this new approach and the usual centrality measures. In addition to this, an analysis of the control of the PageRank of a node is presented in terms of personalization vectors and some sharp analytical results about the limits of this control are included.

Miguel Romance
Centre for Biomedical Technology (CTB)
Technical University of Madrid, Pozuelo de Alarcón, Madrid
miguel.romance@gmail.com

MS21

Inter-Layer Synchronization in Nonidentical Multilayer Networks

Inter-layer synchronization is a dynamical state occurring in multi-layer networks composed of identical nodes. The state corresponds to have all layers synchronized, with nodes in each layer which do not necessarily evolve in unison. So far, the study of such a solution has been restricted to the case in which all layers had an identical connectivity structure. When layers are not identical, the inter-layer synchronous state is no longer a stable solution of the system. Nevertheless, when layers differ in just a few links, an approximate treatment is still feasible, and allows one to gather information on whether and how the system may wander around an inter-layer synchronous configuration. In this Minisyposium, we will report the details of an approximate analytical treatment for a two-layer multiplex, which results in the introduction of an extra inertial term accounting for structural differences. Numerical validation of the predictions highlights the usefulness of our approach, especially for small or moderate topological differences in the intra-layer coupling. Moreover, we identify a non-trivial relationship between the betweenness centrality of the missing links and the intra-layer coupling strength. Finally, by the use of two multiplexed identical layers of electronic circuits in a chaotic regime, we study the loss of inter-layer synchronization as a function of the betweenness centrality of the removed links.

Irene Sendiña-Nadal
Rey Juan Carlos University,
Mostoles, Madrid, Spain
irene.sendina@urjc.es

Inmaculada Leyva
University of Rey Juan Carlos
Madrid, Spain
inmaculada.leyva@urjc.es

Ricardo Sevilla-Escoboza
Centro Universitario de los Lagos
Universidad de Guadalajara
sevillaescoboza@gmail.com

Ricardo Gutierrez
Department of Chemical Physics
The Weizmann Institute of Science
rcd.gutierrez@gmail.com

Javier Buldu
Universidad Politécnica de Madrid, Spain &
Universidad Rey Juan Carlos, Madrid, Spain
javier.buldu@urjc.es

Stefano Boccaletti
CNR-Istituto dei Sistemi Complessi
stefano.boccaletti@isc.cnr.it

MS21

Analysis of Chinese Airline Network As a Multilayer Network

We encapsulate the Chinese Airline Network (CAN) into multi-layer infrastructures via the 'k-core decomposition' method. The network is divided into three layers: Core layer, containing airports of provincial capital cities, is densely connected and sustains most flight flow; Bridge layer, consisting of airports in Tier 2 and Tier 3 cities, mainly connects two other layers; and Periphery layer, comprising airports of remote areas, sustains little flight flow. Moreover, it is unveiled that CAN stays the most robust when low-degree nodes or high flight flow links are removed, which is similar to the Worldwide Airline Network (WAN), albeit less redundant.

Zhen Wang
Qingdao University, Qingdao, China
zhenwang0@gmail.com

MS21

Generalizing the Master Stability Function to Multilayer Networks

The structure of many real-world systems is best captured by networks consisting of several interaction layers. Understanding how a multi-layered structure of connections affects the synchronization properties of dynamical systems evolving on top of it is a highly relevant endeavour in mathematics and physics, and has potential applications to several socially relevant topics, such as power grids engineering and neural dynamics. We present a general framework to assess the stability of the synchronized state in networks with multiple interaction layers, deriving a necessary condition that generalizes the Master Stability Function approach.

Charo I. del Genio
School of Life Sciences
University of Warwick, U.K.
C.I.del-Genio@warwick.ac.uk

MS22

Dimer Dynamics and Degenerate Transversally Intersecting Manifolds

We consider a pharmacological model of dimerisation, i.e., a receptor binding two ligand (drug) molecules. This model is an extension of the well studied target mediated drug disposition model (TMDD) in which the receptor binds to one ligand molecule. It is assumed that the binding is the fastest process. This gives a separation of time scales, which allows us to use geometric singular perturbation theory to analyse these models. In both models, the slow manifold consists of two components, which intersect transversely in the origin. The dimerisation model leads to a degenerate intersection. To analyse such intersection, we consider a general two parameter slow-fast system in which the critical set consists of a one dimensional manifold and a two dimensional manifold, intersecting at the origin. Using geometric desingularisation, we determine the fate of the incoming one dimensional manifold and show that for a subset of the parameter set there is a jump away from the intersection at the origin and away from the critical set. For the remaining parameter set, there is an exchange of stability between the attracting components of the critical set and the direction of the continuation can be expressed in terms of the parameters. The parameters for the dimerisation model fit into the latter category and we will give the approximation of the dynamics in the dimerisation model.

Gianne Derks, Philip J. Aston
University of Surrey
Department of Mathematics
G.Derks@surrey.ac.uk, P.Aston@surrey.ac.uk

Christine Gavin
University of Surrey
c.gavin@surrey.ac.uk

MS22

Beyond Dose Predictions: How Mathematical Pharmacology Supports Drug Development from Target Identification to Clinical Outcomes

As mathematicians we are often looking for interesting AND impactful projects. Drug development presents a plethora of opportunities for the right person. Beyond established methods used for PK/PD and dose selection. We will review the pipeline for those unfamiliar with drug development and discuss industry wide needs for support in target identification, lead optimization, interspecies translation and experimental design. Along this pipeline there are many open questions for mathematicians interested in graph theory, ODEs, PDEs, optimization, control theory, even chaos theory. We will also be discussing how to identify these problems and engage with industry to increase the impact of your work and what to expect once you start on them. A recent case study, utilizing mathematical pharmacology for dose selection of a luminally restricted compound, will used to demonstrate the broader impact using this approach can have outside of the original problem. We will end by discussing challenges to the field and requirements for the brave folk that wish to embark upon it.

Angelean O. Hendrix
GlaxoSmithKline
angelean.hendrix@parexel.com

MS22

Modeling Lung Airway Liquid Dynamics for Hyperosmotic Treatment Design in Cystic Fibrosis

Airway disease in Cystic Fibrosis (CF) is characterized by lung infection, inflammation, and impaired mucociliary clearance (MCC) arising from depletion of the airway surface liquid (ASL) at the organ-scale. Dysfunction in the CF transmembrane conductance regulator protein (CFTR) has been reported to cause cell-scale dysregulation in ion and liquid transport alone and via other transport-related proteins. We have used *in vitro* measurements of ion transport and liquid absorption dynamics in cells with and without CF to develop an ordinary differential equation model of liquid and solute transport in cultured human bronchial epithelia (HBE). Our cell-scale model accurately characterizes transcellular liquid transport in HBE cultures and recapitulates experimental findings of liquid and solute hyperabsorption. From cell-scale predictions we conclude that reduced paracellular integrity is the predominant factor leading to increased liquid and DTPA absorption in CF. At the lung-scale, we have developed a physiologically motivated pharmacokinetic model of the action of hypertonic saline (HS) as an inhaled therapy to improve MCC and reduce absorption of DTPA, and thus airway liquid, in CF. This multi-scale understanding of fluid trafficking in individual patients facilitates the design and optimization of treatment schedules and doses in order to maintain consistent airway hydration.

Robert S. Parker, Matthew Markovetz
Department of Chemical and Petroleum Engineering
University of Pittsburgh
rparker@pitt.edu, mrm163@pitt.edu

Timothy Corcoran
Department of Pulmonary, Allergy, and Critical Care
University of Pittsburgh
corcorante@upmc.edu

MS22

Modelling the Impact of Physicochemical Drug Properties on Drug Reservoirs in the Skin

Treatment of chronically ill patients, such as those suffering from bipolar disorder or drug addiction, often involves long-term drug prescription of potentially harmful drugs (if they reach toxic concentrations in the blood). To maintain drug concentrations within the therapeutic window requires accurate and accessible monitoring which is very challenging. One mechanism that has been proposed is to monitor the drugs non-invasively through the skin. Whilst in principle this is an obvious approach to take, it quickly becomes complicated by the fact that drugs that have circulated for long periods in the body build up reservoirs or archives in the outer skin layers. We have developed a model structure that explores the initial build up of the drug reservoir in the skin and its effect on subsequent drug extraction across the skin. The model system involves systems of coupled PDEs, the parameters of which depend on the physicochemical properties of the drug. This talk will: motivate the choice of model formulation; justify the parameter ranges in terms of properties including lipophilicity, molecular weight and binding; and explore how physicochemical properties affect the model outcomes. It will conclude by discussing implications of the model outcomes and, in response to that, future work.

Jane White
University of Bath
England
k.a.j.white@bath.ac.uk

Jennifer Jones
Department of Mathematical Sciences
j.jones2@bath.ac.uk

Begona Delgado-Charro
Department of Pharmacy and Pharmacology
b.delgado-charro@bath.ac.uk

MS23

Formation of Pseudo-cleavage Furrow during Cell Polarization in C. Elegans

Intracellular polarization, where a cell specifies a spatial axis by segregation of specific factors, is a fundamental biological process. In the early embryo of the nematode worm C. elegans, polarization is often accompanied by deformations of the cortex. It has been suggested that the eggshell surrounding the early embryo plays a role in polarization although its function is not understood. In this work we develop a mathematical model which couples reaction-diffusion equations to a phase field model of the cell cortex and incorporates the eggshell to monitor cortical invaginations during the early development of the C. elegans embryo. We investigate the potential rigidity effect of the geometric constraint imposed by the presence and size of the eggshell on polarization dynamics. Our model suggests that the geometric constraint of the eggshell is essential for proper polarization and the size of the eggshell also affects the dynamics of the polarization. Therefore we conclude that geometric constraint on a cell might affect the dynamics of a biochemical processes.

Betul Aras
Ohio State University
senay.6@osu.edu

Yongcheng Zhou
Department of Mathematics
Colorado State University
yzhou@math.colostate.edu

Adriana Dawes
Department of Mathematics/Department of Molecular Genetics
Ohio State University
dawes.33@osu.edu

Ching-Shan Chou
Department of Mathematics
Ohio State University
chou@math.ohio-state.edu

MS23

Spatial Modeling of Motor Attachment and Detachment

One ingredient of several models for the transport of cargo by multiple motors is the attachment and detachment rates of molecular motors from a microtubule. These rates are usually taken as given constants, but the attachment rate is clearly affected by the local spatial environment and the detachment rate is affected by the force experienced by the motor through its tethering to the cargo. I will report on some ongoing efforts to characterize these attachment and detachment processes through more spatially explicit models. Particular attention will be given to relating the reattachment of a motor to a microtubule to a first passage time problem for the detached motor.

Peter R. Kramer
Rensselaer Polytechnic Institute
Department of Mathematical Sciences
kramep@rpi.edu

Abhishek Choudhary
Rensselaer Polytechnic Institute
abhi.achoudhary@gmail.com

MS23

TheParadoxof Codependence Among Antagonistic Motors in Intracellular Transport

Transport in neurons is intrinsically bidirectional, with each movement modality carried out by molecular motors in either the kinesin (anterograde) or the dynein (retrograde) families. Because all motors are present at a given time there must be competition and/or cooperation among motors that simultaneously bind a single vesicle to nearby microtubules. The prevailing tug-of-war model captures this dynamic, but fails to account for a recently recognized phenomenon: that in many situations, disabling one family of motors somehow inhibits the performance of motors that are working in the opposite direction. In this talk we will survey a few proposed mechanisms that may account for this behavior and will look at recent work that focuses on a potential role played by the helper protein dynactin.

Scott McKinley
Tulane University
scott.mckinley@tulane.edu

MS23

Combining Computational Fluid Dynamics and Electron Tomography to Study the Mechanics of Kinetochore Microtubules

The accurate segregation of chromosomes, and subsequent cell division, in Eukaryotic cells is achieved by the interactions of an assembly of microtubules (MTs) and motor-proteins, known as the mitotic spindle. We use a combination of our computational platform for simulating cytoskeletal assemblies and our structural data from high-resolution electron tomography of the mitotic spindle, to study the kinetics and mechanics of MTs in the spindle, and their interactions with chromosomes during chromosome segregation in the first cell division in C.elegans embryo. We focus on kinetochore MTs, or KMTs, which have one end attached to a chromosome. KMTs are thought to be a key mechanical component in chromosome segregation. Using exploratory simulations of MT growth, bending, hydrodynamic interactions, and attachment to chromosomes, we propose a mechanical model for KMT-chromosome interactions that reproduces observed KMT length and shape distributions from electron tomography. We find that including detailed hydrodynamic interactions between KMTs is essential for agreement with the experimental observations.

Ehssan Nazockdast
Courant Institute of Mathematical Sciences
New York University
enazockdast@simonsfoundation.org

Sebastian Fürthauer
Flatiron Institute, Center for Computational Biology
sfuerthauer@simonsfoundation.org

Stefanie Redemann, Thomas Müller-Reichert
Experimental Centre, Medical Faculty Carl Gustav Carus,
Technische Universität Dresden, 01307 Dresden, Germany
stefanie.redemann@mailbox.tu-dresden.de,
mueller-reichert@tu-dresden.de

Michael Shelley
Group Leader in Biophysical Modeling Group,
Center for Computational Biology, Simons Foundation
mshelley@simonsfoundation.org

MS24

Optimal Control Re-Examined Using the Geometric Methods of Dynamical Systems

In this talk, we look at optimal control from the perspective of dynamical systems, and demonstrate how this geometric understanding may help us in the optimal design of controllers. We start with analyzing the stable and unstable manifolds of the Hamilton equation arising from the Pontryagin Maximum Principle (PMP) in optimal control. We demonstrate through numerical simulations how the trajectories of the Hamilton boundary value problem (BVP) behave with different time horizon, control constraints, and end-time state conditions. Due to difficulties in solving the BVP in applications, optimal controller designs are often carried out using model predictive control (MPC). We analyze the closed-loop systems arising from MPC and from PMP through the example of an optimal adaptive cruise controller, where we project the trajectories of the Hamilton equations into the phase plane and compare them with the trajectories arising from MPC. With a geometrical understanding of the optimal control, we design an optimal connected cruise controller using MPC, where the equipped vehicle exploits motion information receives from multiple vehicles ahead via vehicle-to-vehicle communication. We consider state and control constraints of the vehicle and use state predictors to compensate for the communication delay in the controller.

Jin Ge
University of Michigan, Ann Arbor
gejin@umich.edu

Gabor Orosz
University of Michigan, Ann Arbor
Department of Mechanical Engineering
orosz@umich.edu

MS24

A System-Level Approach to Controller Synthesis

Biological and advanced cyberphysical control systems often have limited, sparse, uncertain, and distributed communication and computing in addition to sensing and actuation. Fortunately, the corresponding plants and performance requirements are also sparse and structured, and this must be exploited to make constrained controller design feasible and tractable. We introduce a new "system level" (SL) approach involving three complementary SL elements. System Level Parameterizations (SLPs) generalize state space and Youla parameterizations of all stabilizing controllers and the responses they achieve, and combine with System Level Constraints (SLCs) to parameterize the largest known class of constrained stabilizing controllers that admit a convex characterization, generalizing quadratic invariance (QI). We further provide a catalog of useful SLCs, most importantly including sparsity, delay, and locality constraints on both communication and computing internal to the controller, and external system performance. The resulting System Level Synthesis (SLS) problems that arise define the broadest known class of constrained optimal control problems that can be solved using convex programming. An example illustrates how this system level approach can systematically explore tradeoffs in controller performance, robustness, and synthesis/implementation complexity.

Nikolai Matni
California Institute of Technology
nmatni@caltech.edu

Yuh-Shyang Wang, John Doyle
Caltech
Department of Control and Dynamical Systems
yw4ng@caltech.edu, doyle@cds.caltech.edu

MS24

Automata Theory and Dynamic Programming

We investigate the synthesis of optimal controllers for continuous-time and continuous-state systems under behavioral specifications. The specification is expressed as a deterministic, finite automaton (the specification automaton) with transition costs, and the optimal system behavior is captured by a cost function that is integrated over time. We construct a dynamic programming problem over the product of the underlying continuous-time, continuous-state system and the discrete specification automaton. To solve this dynamic program, we propose controller synthesis algorithms based on Approximate Dynamic Programming (ADP) for both linear and nonlinear systems under temporal logic constraints. We argue that ADP allows treating the synthesis problem directly, without forming expensive discrete abstractions. We show that, for linear systems under co-safe temporal logic constraints, the ADP solution reduces to a single semidefinite program. Furthermore, we will also show how to extend these techniques to perform safe data-driven controller learning, and learning by expert demonstrations—thereby incorporating data and side information in a provably safe way.

Ivan Papusha
University of Texas
ipapusha@utexas.edu

Jie Fu
Worcester Polytechnic Institute
jfu2@wpi.edu

Min Wen
University of Pennsylvania
wenm@seas.upenn.edu

Ufuk Topcu
University of Texas

utopcu@utexas.edu

Richard Murray
Control and Dynamical Systems
California Institute of Technology
murrayrm@cds.caltech.edu

MS24

Learning Model Predictive Control for Iterative Tasks

Learning Model Predictive Control (LMPC) is a control technique for system performing iterative tasks. In LMPC, the data collected from each task execution are exploited to improve the system performance. A safe set and a terminal cost function are used to guarantee recursive feasibility and improving performance for the closed-loop system. In this talk, we discuss the LMPC design, how to construct the safe set and the terminal cost from data. We show that the proposed LMPC converges to a local optimal trajectory. The effectiveness of the LMPC will be demonstrated by experimental results on a self-driving race car.

Ugo Rosolia, Francesco Borrelli
University of California, Berkeley
ugo.rosolia@berkeley.edu, fborrelli@berkeley.edu

MS25

Algorithms for Processing the Labeled Conley Index

Conley index theory has proven to be a powerful tool for automating the rigorous exploration of dynamical systems. When searching for highly complicated dynamics, however, the Conley index may also become highly complicated, and difficult to interpret or use in rigorous arguments. I will present an automated approach to processing Conley index information for discrete-time dynamical systems, joint work with Sarah Day and Rodrigo Treviño. This approach produces a topologically semi-conjugate symbolic dynamical system whose topological entropy serves as a lower bound for that of the system under study. I will describe several applications and modifications of this approach, culminating in recent work with Sarah Day which uses sofic shifts to in some sense capture as much information from the index as possible.

Rafael Frongillo
University of Colorado, Boulder
raf@colorado.edu

MS25

Advances on Wright's Conjecture: Counting and Discounting Periodic Orbits in a Delay Differential Equation

Despite the deceptively simple appearance of Wright's equation: $y'(t) = -\alpha y(t-1)[1+y(t)]$, a complete understanding of its global dynamics remains out of grasp. A long-standing conjecture claims that Wright's equation does not have any periodic orbits when $\alpha < \pi/2$ and there is a unique slowly oscillating periodic orbit when $\alpha > \pi/2$. In this talk I will present recent progress on this conjecture. In particular I will discuss applications of rigorous numerics to study the Hopf bifurcation at $\alpha = \pi/2$, as well as the asymptotic stability of periodic orbits for mesoscopic values of α.

Jonathan C. Jaquette
Rutgers University
jaquette@math.rutgers.edu

Jean-Philippe Lessard
Université Laval
jean-philippe.lessard@mat.ulaval.ca

Konstantin Mischaikow
Department of Mathematics
Rutgers, The State University of New Jersey
mischaik@math.rutgers.edu

Jan Bouwe Van Den Berg
VU University Amsterdam
Department of Mathematics
janbouwe@few.vu.nl

MS25

Rigorous Continuation of Periodic Orbits and Validation of Hopf Bifurcations

Periodic solutions to ODEs are hard to determine by direct calculation but are relatively easy to compute numerically. By means of a computer, it is also possible to continue a branch of periodic solutions in case of parameter dependency of the vector field. In this talk, the mathematically rigorous validation of such "numerical" branches of periodic solutions will be presented. The method relies on the application of radii polynomials to polynomial vector fields of any order. An interesting feature of the presented method is the generality of the approach with respect to dimensionality: the presented bounds do not suffer greatly in higher dimensions. Furthermore, ongoing research on rigorous validation of Hopf bifurcations will be presented, since Hopf bifurcations are a common source of periodic solutions. The first goal of this research is to validate, in the same general setting of polynomial vector field of any order and dimensionality, the Hopf bifurcation point. The second goal is to develop techniques for the validated continuation of branches of cycles starting at a validated Hopf bifurcation point.

Elena Queirolo
Vrije Universiteit Amsterdam
e.queirolo@vu.nl

MS25

Validated Saddle-node Bifurcations and Applications to Lattice Dynamical Systems

The use of rigorous verification methods is a powerful tool which permits progress in the analysis of dynamical processes that is not possible using purely analytical techniques. In this talk we describe a set of tools for branch validation, which allows for the rigorous verification of branch behavior, bifurcation, and solution index on branches generated through a saddle-node bifurcation. While the presented methodology can be applied in a variety of settings, we illustrate the use of these tools in the context of materials science. In particular, lattice models have been proposed as a more realistic reflection of the behavior of materials than traditional continuum models, since they can account for phenomena such as pinning. However, in the context of bifurcation theory, questions about lattice dynamical systems are significantly harder to answer than for a continuum model. We show that computer-assisted proof techniques can be used to answer some of these questions, and apply these tools to the discrete Allen-Cahn equation. This provides results on the existence of branches of mosaic solutions and their robustness as it relates to grain size. We also demonstrate that there are situations in which classical continuation methods can fail to identify the correct branching behavior.

Evelyn Sander
George Mason University
esander@gmu.edu

Thomas Wanner
George Mason University
Department of Mathematical Sciences
twanner@gmu.edu

MS26

Data Assimilation Algorithms for Geophysical Models and Charney's Conjecture

We propose data assimilation algorithms for the Bénard convection problem and the 3D Planetary Geostrophic model of ocean, that employ coarse spatial mesh observations of the temperature alone. We show that the algorithms converge to the reference solution for both the Bénard problem in porous media and the 3D Planetary Geostrophic model cases. On the other hand, recent numerical results indicate that the algorithm doesn't converge for the Bénard model. This justifies an earlier conjecture of Charney which states that temperature history of the atmosphere, for certain simple atmospheric models, determines all other state variables.

Aseel Farhat
Department of Mathematics
University of Virginia
af7py@virginia.edu

Evelyn Lunasin
United States Naval Accademy
lunasin@usna.edu

Edriss S. Titi
Texas A&M University
Weizmann Institute of Science
titi@math.tamu.edu, edriss.titi@weizmann.ac.il

MS26

Numerical Approximation of a Data Assimilation Algorithm by a Post-processing Galerkin Method

We consider a data assimilation algorithm for recovering the exact value of a reference solution of the two-dimensional Navier-Stokes equations, by using continuous in time and coarse spatial observations. The algorithm is given by an approximate model which incorporates the observations through a feedback control (nudging) term. We obtain an analytical uniform in time estimate of the error committed when numerically solving this approximate model by using a post-processing technique for the spectral Galerkin method, inspired by the theory of approximate inertial manifolds. This is a joint work with C. Foias and E. S. Titi.

Cecilia F. Mondaini, Ciprian Foias
Texas A&M University
cfmondaini@math.tamu.edu, fioas@math.tamu.edu

Edriss S. Titi
Texas A&M University
Weizmann Institute of Science
titi@math.tamu.edu, edriss.titi@weizmann.ac.il

MS26

Synchronization of Chaotic Dynamical Systems Using Time-Averaged Partial Observations of the Phase Space

We study the synchronization of chaotic systems when the coupling between them contains both time averages and stochastic noise. Our model dynamics are given by the Lorenz equations which are a system of three ordinary differential equations in the variables X, Y and Z. Our theoretical results show that coupling two copies of the Lorenz equations using a feedback control which consists of time averages of the X variable leads to exact synchronization provided the time-averaging window is known and sufficiently small. In the presence of noise the convergence is to within a factor of the variance of the noise. We also consider the case when the time-averaging window is not known and show that it is possible to tune the feedback control to recover the size of the time-averaging window. Further numerical computations show that synchronization is more accurate and occurs under much less stringent conditions than our theory requires.

Jordan Blocher
University of Nevada Reno
jordanblocher@gmail.com

Vincent R. Martinez
Tulane University
vmartin6@tulane.edu

Eric Olson
UNR
ejolson@unr.edu

MS26

Determining the Global Dynamics of the 2D Navier-Stokes Equations by 1D ODE

One of the main characteristics of infinite-dimensional dissipative evolution equations, such as the Navier-Stokes equations and reaction-diffusion systems, is that their long-time dynamics is determined by finitely many parameters – finite number of determining modes, nodes, volume elements and other determining interpolants. In this talk I will show how to explore this finite-dimensional feature of the long-time behavior of infinite-dimensional dissipative systems to design finite-dimensional feedback control for stabilizing their solutions. Notably, it is observed that this very same approach can be implemented for designing data assimilation algorithms of weather prediction based on discrete measurements. In addition, I will also show that the long-time dynamics of the Navier-Stokes equations can be imbedded in an infinite-dimensional dynamical system that is induced by an ordinary differential equations, named *determining form*, which is governed by a globally Lipschitz vector field. Remarkably, as a result of this machinery I will eventually show that the global dynamics of the Navier-Stokes equations is be determining by only one parameter that is governed by an ODE. The Navier-Stokes equations are used as an illustrative example, and all the above mentioned results equally hold to other dissipative evolution PDEs, in particular to various dissipative

reaction-diffusion systems and geophysical models.

Edriss S. Titi
Texas A&M University
Weizmann Institute of Science
titi@math.tamu.edu, edriss.titi@weizmann.ac.il

Ciprian Foias
Texas A&M University
fioas@math.tamu.edu

Michael S. Jolly
Indiana University
Department of Mathematics
msjolly@indiana.edu

Dan Lithio
Indiana University
dlithio@gmail.com

MS27

Independent Noise Synchronizing Population Rhythms of Networks of Pulse-Coupled Oscillators

The coherent dynamics of coupled oscillators have been studied extensively. In the neuronal networks of the brain such coherence is observed to generate a rich variety of rhythms, among them the well-studied γ-rhythm. It has been suggested that coherence across different brain areas may play an important role in the communication between these areas. Motivated by the observation of the coexistence of different γ-rhythms in the olfactory system and of the coherence of γ-rhythms across different brain areas, we consider the interaction between networks of pulse-coupled inhibitory neurons, with each network supporting its own γ-rhythm. We focus on the effect of noise on the synchronization of coupled networks. Surprisingly, we find that different γ-rhythms, each corresponding to the coherent activity of neurons in one of the coupled networks, can become synchronized by noise, even if that noise is completely uncorrelated between different neurons. By reducing the coherent dynamics of the two networks to an iterated map we show that key for the enhanced synchronization is the noise-induced phase heterogeneity, which allows the faster network to suppress the spiking of a fraction of the neurons in the slower network. The resulting synchronization can increase the learning speed of neurons that read the coupled networks via synapses exhibiting spike-timing-dependent plasticity. Supported by NSF-CMMI 1435358

John Meng, Xize Xu
Northwestern University
hongyumeng2013@u.northwestern.edu,
xizexu2016@u.northwestern.edu

Hermann Riecke
Applied Mathematics
Northwestern University
h-riecke@northwestern.edu

MS27

Distance-Dependent Edge-Correlations and Synchrony in Neuronal Networks

To examine how network microstructure and global structure network patterns can influence synchronization in a neuronal network, we developed a network model that combines correlations among edges with distance-dependent connection probability. This model is an extension of the SONET model [Zhao et al, 2011] that adds spatial structure by allowing heterogeneous first order connectivity statistics. The second order connectivity statistics, i.e., the covariances among the edges that determine the frequency of convergent, divergent, chain, and reciprocal connections, remain homogeneous across the network. We use this model to generate ring models with period spatial structure that is combined with the SONET microstructure. We analyze these networks to predict how the SONET parameters as well as the global parameters predict synchrony across the network.

Duane Nykamp
School of Mathematics
University of Minnesota
nykamp@umn.edu

Samantha Fuller
University of Minnesota
fulle363@umn.edu

MS27

Granger Causality in Sparse Neuronal Network

Granger causality (GC) is a mathematical tool to reveal linear dependencies between random variables. It has been widely used in neuroscience to examine the signals to show the effective connectivity between neurons in a network. Recent computational research has shown that GC can successfully reconstruct neuronal network provided either voltage trace or spike train of all the neurons. But it is generally unrealistic experimentally. In this talk, we will show that for a sparse neuronal network, only partial recordings are needed to recover the local network structure, and the possible cause of error is also analyzed.

Yangyang Xiao
New York University Abu Dhabi
yx742@nyu.edu

MS27

A Probability Polling State of Neuronal Systems Underlying Maximum Entropy Coding Principle

How to extract information from exponentially growing recorded neuronal data is a great scientific challenge. In recent experiments, it has been found that the second order maximum entropy model, by using only firing rates and second order correlations of neurons as constraints, can well capture the observed distribution of neuronal firing patterns in many neuronal networks, thus, conferring its great advantage in that the degree of complexity in the analysis of neuronal activity data reduces drastically from $O(2^n)$ to $O(n^2)$, where n is the number of neurons under consideration. In this talk, we address the question of what kind of dynamical states of neuronal networks allows the network to possess a coding scheme dictated by the Maximum Entropy Principle (MEP). For asynchronous neuronal networks, when considering the probability increment of a neuron spiking induced by other neurons, we found a probability polling (p-polling) state that underlies the success of the second order maximum entropy model. We show that this p-polling state can arise in vitro and in vivo. Our theoretical analysis of the p-polling state and its relationship to MEP provides a new perspective to the information coding of neuronal network dynamics in the brain.

Douglas Zhou
Shanghai Jiao Tong University
zdz@sjtu.edu.cn

Zhiqin John Xu
Abu Dhabi and Courant Institute
New York University
zhiqinxu@nyu.edu

David Cai
Courant Institute for Mathematical Sciences, NYU
Shanghai Jiao-Tong University
cai@cims.nyu.edu

MS28

Connecting Hyperbolic Geometry to Kuramoto Oscillator Systems; New Classes of Gradient Phase Models and Completely Integrable Dynamics

Kuramoto oscillator networks have the special property that their time evolution is constrained to lie on 3D orbits of the Möbius group acting on the N-fold torus T^N which explains the $N-3$ constants of motion discovered by Watanabe and Strogatz. The dynamics for phase models can be further reduced to 2D invariant sets in T^{N-1} which have a natural geometry equivalent to the unit disk $\mathbb{D}$ with hyperbolic metric. We show that the classic Kuramoto model with order parameter Z_1 (the first moment of the oscillator configuration) is a gradient flow in this metric with a unique fixed point on each generic 2D invariant set, corresponding to the hyperbolic barycenter of an oscillator configuration. This gradient property makes the dynamics especially easy to analyze. We exhibit several new families of Kuramoto oscillator models which reduce to gradient flows in this metric; some of these have a richer fixed point structure including non-hyperbolic fixed points associated with fixed point bifurcations.

Jan Engelbrecht
Department of Physics, Boston College
jan@bc.edu

MS28

Frequency Spiral

We study the dynamics of coupled phase oscillators on a two-dimensional Kuramoto lattice with periodic boundary conditions. For coupling strengths just below the transition to global phase-locking, we find localized spatiotemporal patterns that we call frequency spirals. These patterns cannot be seen under time averaging; they become visible only when we examine the spatial variation of the oscillators'instantaneous frequencies, where they manifest themselves as two-armed rotating spirals. In the more familiar phase representation, they appear as wobbly periodic patterns surrounding a phase vortex.Unlike the stationary phase vortices seen in magnetic spin systems, or the rotating spiral waves seen in reaction-diffusion systems, frequency spirals librate: the phases of the oscillators surrounding the central vortex move forward and then backward, executing a periodic motion with zero winding number. We construct the simplest frequency spiral and characterize its properties using analytical and numerical methods. Simulations show that frequency spirals in large lattices behave much like this simple prototype.

Bertrand Ottino-Loffler
Center for Applied Mathematics
Cornell University
bjo34@cornell.edu

MS28

Interplay of Coupling and Common Noise at the Transition to Synchrony in Oscillator Populations

There are two ways to synchronize oscillators: by coupling and by common forcing, which can be pure noise. By virtue of the Ott-Antonsen ansatz for sine-coupled phase oscillators, we obtain analytically tractable equations for the case where both coupling and common noise are present. While noise always tends to synchronize the oscillators, the repulsive coupling can act against synchrony, and we focus on this nontrivial situation. For identical oscillators, the fully synchronous state remains stable for small repulsive coupling; moreover it is an absorbing state which always wins over the asynchronous regime. For oscillators with a distribution of natural frequencies, we report on a counter-intuitive effect of dispersion (instead of usual convergence) of the oscillators frequencies at synchrony; the latter effect disappears if noise vanishes.

Arkady Pikovsky
Department of Physics and Astronomy
University of Potsdam, Germany
pikovsky@uni-potsdam.de

Denis S. Goldobin
Institute for Physics, University of Potsdam
Potsdam, Germany
Denis.Goldobin@gmail.com

Michael Rosenblum
Potsdam University
Department of Physics and Astronomy
mros@uni-potsdam.de

Anastasyia Pimenova
Institute of Continuous Media Mechanics, Ural Brahch of RAS
Perm, Russia
skvp@list.ru

MS28

Dynamics of Weakly Inhomogeneous Oscillator Populations: Perturbation Theory on Top of WatanabeStrogatz Integrability

As has been shown by Watanabe and Strogatz (WS) (1993, Phys. Rev. Lett. 70, 2391), a population of identical phase oscillators, sine-coupled to a common field, is a partially integrable system: for any ensemble size its dynamics reduce to equations for three collective variables. Here we develop a pertur- bation approach for weakly nonidentical ensembles. We calculate corrections to the WS dynamics for two types of perturbations: those due to a distribution of natural frequencies and of forcing terms, and those due to small white noise. We demonstrate that in both cases, the complex mean field for which the dynamical equations are written is close to the Kuramoto order parameter, up to the leading order in the perturbation. This supports the validity of the dynamical reduction suggested by Ott and Antonsen (2008, Chaos 18, 037113) for weakly inhomogeneous populations.

Vladimir Vlasov
Istituto Italiano di Tecnologia

vladimir.vlasov@iit.it

Michael Rosenblum
Potsdam University
Department of Physics and Astronomy
mros@uni-potsdam.de

Arkady Pikovsky
Department of Physics and Astronomy
University of Potsdam, Germany
pikovsky@uni-potsdam.de

MS29

The Motion of a Droplet for the Stochastic Mass-conserving Allen-Cahn Equation

We study the stochastic mass-conserving Allen-Cahn equation posed on a smoothly bounded domain of R^2 with additive, spatially smooth, space-time noise. This equation describes the stochastic motion of a small almost semicircular droplet attached to domain's boundary and moving towards a point of locally maximum curvature. We apply Itô calculus to derive the stochastic dynamics of the center of the droplet by utilizing the approximately invariant manifold introduced by earlier by Alikakos, Chen and Fusco for the deterministic problem. In the stochastic case depending on the scaling, the motion is driven by the change in the curvature of the boundary and the stochastic forcing. Moreover, under the assumption of a sufficiently small noise strength, we establish stochastic stability of a neighborhood of the manifold of boundary droplet states in the L^2- and H^1-norms, which means that with overwhelming probability the solution stays close to the manifold for very long time-scales.

Peter W. Bates
Michigan State University
Department of Mathematics
bates@math.msu.edu

Dimitra Antonopoulou
University of Chester
d.antonopoulou@chester.ac.uk

Dirk Blömker
Universitat Augsburg
Germany
dirk.bloemker@math.uni-augsburg.de

Georgia Karali
University or Crete
gkarali@uoc.gr

MS29

Stochastic Modulation Equations on Unbounded Domains

The reduction of complicated dynamics on large domains via modulation equations is a well known tool to reduce the complexity of the model close to a change of stability. While for deterministic models this is a well established theory, there are hardly any results for stochastic models on unbounded domains. In the talk we consider the approximation via modulation equations for nonlinear SPDEs on unbounded domains with additive space time white noise. As a first example we study the stochastic Swift-Hohenberg equation on the whole real line, where due to the weak regularity of solutions the all standard methods for modulation equations fail. As a side product we verify local existence and uniqueness of the stochastic Swift-Hohenberg and the complex Ginzburg Landau equation on the whole real line in weighted spaces that allow for growth at infinity of solutions. Moreover we use energy estimates to show that solutions of the Ginzburg-Landau equation are Hlder-continuous, which just gives enough regularity to proceed with the error estimates.

Dirk Blömker
Universitat Augsburg
Germany
dirk.bloemker@math.uni-augsburg.de

Guido Schneider
University of Stuttgart
Department of Mathematics
guido.schneider@mathematik.uni-stuttgart.de

Luigi A. Bianchi
TU Berlin
luigiamedeo.bianchi@gmail.com

MS29

Stochastic Dynamics: Data-Driven Information Extraction via Effective Reduction

Dynamical systems arising in engineering and science often evolve under random fluctuations and multiple scales. The random fluctuations may be Gaussian or non-Gaussian described by Brownian motion or α-stable Levy motion, respectively. Stochastic dynamical systems with α-stable Levy motions have attracted a lot of attention recently. The non-Gaussianity index α is a significant indicator for various dynamical behaviors. The speaker will present recent work on data assimilation and extraction of dynamical behaviors (e.g., transitions, mean residence time, escape probability), via effective approximations, such as slow manifold, homogenization, and averaging, for stochastic dynamical systems with non-Gaussian Levy noise.

Jinqiao Duan
Illinois Institute of Technology
Department of Applied Mathematics
duan@iit.edu

MS29

Couple Periodic-patches of a Stochastic Microscale to Predict Emergent Macroscale Dynamics

Molecular simulations, while in principle deterministic on the microscale, are chaotic and so effectively stochastic on meso/macro-scales. Many other microscale simulations are directly stochastic. Furthermore, as for many microscale systems, molecular simulations are much the easiest to code with periodic boundary conditions in space. We seek to distribute many small periodic-patches of such stochastic microscale simulators over a macroscale grid. Then the research aim is find a coupling between the small patches in order to effectively and cheaply simulate the macroscale dynamics. A stochastic slow manifold analysis of the system of stochastic periodic-patches indicates that a proportional control applied within action regions of each patch can be effective. The analysis suggest Lagrange interpolation of core-patch averages provides a useful control. A pilot implementation of the coupling to a small triply-periodic patch of atomistic simulation indicates that the scheme can usefully predict the emergent macroscale.

Anthony J. Roberts
University of Adelaide
anthony.roberts@adelaide.edu.au

MS30

Nonlinear Dynamics in Optimal Communication Waveforms

Standard methods of communication theory are used to derive the optimal communications waveform corresponding to a simple infinite impulse response (IIR) matched filter. Surprisingly, we find that the resulting waveform is chaotic. Specifically we presume a simple linear RLC matched filter and derive a fixed basis function that maximize the receiver signal-to-noise performance. A communication waveform is constructed by linear superposition of the fixed basis functions with binary weight at each symbol time. It is shown that the resulting waveform has an embedded shift, implying the waveform is chaotic. Furthermore, the optimal waveforms are naturally generated by a piecewise linear manifold oscillator that is easily realized in a hybrid analog-digital electronic circuit. We extrapolate from this result and argue that the optimal communication waveform for any stable IIR filter is similarly chaotic. If true, this conjecture implies nonlinear dynamics and chaos are essential to a full understanding of modern communication theory.

Ned J. Corron, Jonathan Blakely
U.S. Army AMRDEC
ned.j.corron.civ@mail.mil,
jonathan.n.blakely.civ@mail.mil

MS30

Recent Discoveries in Solvable Chaotic Systems

Exact solutions are rare in the study of chaotic dynamics, but some examples do exist. Recently, analytic chaotic solutions have been found for a class of hybrid dynamical systems, which has allowed for new methods of exploitation of chaos. The key characteristic of these chaotic solutions is an analytic expression for the waveform that can be written as an infinite sum of copies of a single basis function, enabling the use of well established, conventional communication theory, and signal processing. Here we describe a solvable 2nd order chaotic differential equation with a circuit implementation that can be used for acoustic detection and ranging. Specifically, we highlight the benefits of using solvable chaos in application such as matched filtering and compressibility for efficient waveform storage. Furthermore, we detail more recent discoveries in manipulating hybrid systems that bring rise to new phenomena. In particular, we describe how solvability is preserved even in the presence of complex clock patterns, the dynamics of hybrid systems with a multi-level discrete state, as well as a generalization of the discrete state rule which allows for a period doubling route to chaos.

Marko S. Milosaviljevic
US Army RDECOM
marko.s.milosavljevic.ctr@mail.mil

MS30

Circuit Implementation of Generalized Projective Synchronization for Bistatic Radar Applications

An electronic implementation of the generalized projective synchronization using the Lorenz chaotic oscillator is shown. The potential of this synchronization approach is illustrated for the bistatic radar synchronization. The setup includes a Lorenz oscillator at the transmitter and another at the receiver. Due to the system and space propagation losses, the response oscillator must accept the scaled version of the transmitted chaotic waveform as the driver variable. Since the scaling factor is not known a priori, we propose the generalized projective synchronization. A circuit implementation of this approach is presented where the transmitted waveform is replicated at the receiver. The proposed synchronization is found to be very robust for changes in the control parameters of the oscillators. The application of this approach is illustrated for the bistatic radar system where synchronization is necessary to obtain the range-Doppler information of the target. The short time cross-correlation between the transmitted and the synchronized waveforms is very high and the sidelobes are below -15 Db. This indicates the advantages of chaotic synchronization compared to other traditional synchronization techniques utilized for bistatic radars.

Chandra S. Pappu
Union College
pappuc@union.edu

Benjamin C. Flores
University of Texas at El Paso
Electrical and Computer Engineering
bflores@utep.edu

MS30

A Demonstration Wireless Exact Solvable Chaotic Communication System

A wireless communication system based on an exact solvable chaotic equation has been demonstrated. The system consists of a data input section, a chaos oscillator controller, an exact solvable chaotic oscillator, an AM wireless communication system, a matched filter and a data output section. ST microcontrollers are used to input data (data input section) to and output data (data output section) from the communication system. The exact solvable chaotic oscillator has a fundamental frequency of 18 kHz. It produces a baseband chaotic signal using a single transistor sinusoidal oscillator circuit with a signum function based nonlinearity. The oscillator is controlled into two distinct orbits, representing 1s and 0s, using proportional feedback control. A standard AM transmitter up converts the chaos modulated signal onto a 2.3 GHz carrier for wireless transmission to a receiver that down converts it back to baseband. A matched filter specifically designed for the exact solvable chaotic oscillator is then used to recover the information from the received signal.

Keaton Rhea, Andrew Muscha, Remington Harrison,
Frank Werner, Robert Dean
Auburn University
bkr0001@tigermail.auburn.edu, azm0043@auburn.edu,
rch0012@tigermail.auburn.edu,
ftw0001@tigermail.auburn.edu, deanron@auburn.edu

Darren Boyd
NASA-MSFC
darren.r.boyd@nasa.gov

MS31

Nonlinear Dynamics of Vehicle Networks with

Long Range Vehicle-to-vehicle Communication

The development and deployment of connected and automated vehicles is currently capturing the interest of academia and industry. These vehicles must be able to interact in a complex environment of vehicular traffic consisting of vehicles of different levels of autonomy including conventional human-driven vehicles. Such an environment is full of nonlinearities, time delays and uncertainties. We use bifurcation analysis to characterize large scale patterns in traffic such as stop-and-go jams, and then use this insight to design control algorithms for connected and autonomous vehicles. We demonstrate that by inserting these vehicles into the flow of conventional vehicles allows us to change the large scale traffic dynamics even for low penetrations of connected and autonomous vehicles.

Sergei S. Avedisov
University of Michigan, Ann Arbor
avediska@umich.edu

Gabor Orosz
University of Michigan, Ann Arbor
Department of Mechanical Engineering
orosz@umich.edu

MS31

Emergent Task Differentiation on Network Filters

In this talk, we analyze the emergence of task differentiation in a model complex system, characterized by an absence of hierarchical control, yet able to exhibit coordinated behavior and collective function. The analysis focuses on linear network filters, i.e., networks of coupled linear oscillators with a differentiated steady-state response to exogenous harmonic excitation. It demonstrates how an optimal allocation of excitation sensitivities across the network nodes in a condition of resonance may be constructed either using global information about the network topology and spectral properties or, alternatively, through the iterated dynamics of a nonlinear, nonsmooth learning paradigm that only relies on local information within the network. Explicit conditions on the topology and desired resonant mode shape are derived to guarantee local asymptotic stability of fixed points of the learning dynamics. The analysis also demonstrates the possibly semi-stable nature of the fixed point with all zero excitation sensitivities, a condition of system collapse that can be reached from an open set of initial conditions, but that is unstable under the learning dynamics. Theoretical and numerical results also show the existence of periodic responses, as well as of connecting dynamics between fixed points, resulting in recurrent metastable behavior and noise-induced transitions along cycles of such connections.

Mehdi Saghafi
University of Illinois at Urbana-Champaign
mehdi.saghafi@gmail.com

Harry Dankowicz
University of Illinois at Urbana-Champaign
Department of Mechanical Science and Engineering
danko@illinois.edu

Whitney Tabor
University of Connecticut
whitneytabor@zoho.com

MS31

A Delay-Based Controller Design Using Lambert W function in a Multi-Agent Consensus Dynamics

A class of linear time invariant consensus dynamics is considered in this study, where agents' decision making is affected by a time delay. Here we focus on achieving fast consensus by means of pole placement. Specifically, we propose a delay-based controller for each agent, whereby this controller structure enables a decomposition of the system characteristic equation, which is then effectively analyzed with established tools based on Lambert W function. We show that the delay-based controller can easily be tuned to place system rightmost roots to achieve fast consensus for a given delay in the system, and present case studies where the delay is time-varying and how the delay-based controller performs on the consensus dynamics.

Adrian Ramirez
Northeastern University
Boston, MA
a.ramirezlopez@northeastern.edu

Min Hyong Koh
Northeastern University
koh.m@husky.neu.edu

Rifat Sipahi
Department of Mechanical and Industrial Engineering
Northeastern University
rifat@coe.neu.edu

MS31

Stability Charts for Continua Subjected to Delayed Feedback

The lecture provides a summary of engineering problems where the underlying mechanical model is a controlled continuum and the corresponding mathematical model is a partial differential equation with delayed boundary conditions. The examples include the stabilization of rockets with delayed follower forces, material forming processes like boring or deep drilling, and electroacoustics. The detailed derivation of the stability chart of the electroacoustic problem is presented. The characteristic roots of the linear system do not depend continuously on the delay parameters. The physical interpretation of these mathematical results require special considerations. The possible bifurcations are also checked along the stability limits, and the vibration frequencies of the possible primary and secondary Hopf and double Hopf bifurcations are calculated.

Li Zhang
Nanjing University of Aeronautics and Astronautics
zhangli@nuaa.edu.cn

Gabor Stepan
Department of Applied Mechanics
Budapest University of Technology and Economics
stepan@mm.bme.hu

MS32

Dynamics Near Cubic Homoclinic Tangencies in Symplectic Maps

We study the orbit behavior near cubic homoclinic tangencies in two-dimensional symplectic maps. We distinguish two types of cubic homoclinic tangencies, and each type gives different first return maps derived to diverse conservative cubic Hénon maps with quite different bifurcation diagrams. In this way, we establish the structure of bifurcations of periodic orbits in two parameter general unfoldings generalizing to the conservative case the results previously obtained for the dissipative case.

Marina Gonchenko
University of Barcelona
mgonchenko@gmail.com

Sergey Gonchenko
N.I.Lobachevsky Nizhny Novgorod University
sergey.gonchenko@mail.ru

Ivan Ovsyannikov
University of Bremen, Germany
Ivan.I.Ovsyannikov@gmail.com

MS32

Mixed Dynamics in Planar Reversible Diffeomorphisms

Existence of open regions of structural instability was a crucial discovery for Bifurcation Theory. In this sense, the pioneering works of Newhouse [1970, 1979] were seminal: there exist open regions in the space of dynamical systems where systems with homoclinic tangencies are dense (in the C^r-topology, $r \geq 2$). A particular case where such domains exist in any neighbourhood around a planar diffeomorphism having an homoclinic tangency. This tangency is typically quadratic and constitutes a codimension-1 bifurcation. From the 70s there have been important contributions to extend the work of Newhouse: Shilnikov, Gavrilov, Palis, Viana, Duarte, Tedeschini- Lalli, Yorke, Gonchenko, Turaev, Romero, and many others. One of the main difficulties studying such regions in the space of dy- namical systems is its extreme richness. This means that to provide a complete description of their dynamics becomes a very difficult target. From the works above it was suggested as one of the most important properties in these Newhouse regions the coexistence of infinitely many periodic orbits of different types of stability (attracting, repelling, saddle and elliptic). This leads to the concept of the so-called Mixed dynamics. The aim of this work is to present some results and techniques "à la Shilnikov" proving mixed dynamics for reversible diffeos. It is based on papers with A. Delshams, S., V. and M. Gonchenko and O. Sten'kin.

J. Tomas Lazaro
Universitat Politecnica de Catalunya
jose.tomas.lazaro@upc.edu

MS32

On Taken's Last Problem: Times Averages for Heteroclinic Attractors

In this talk, I will discuss some properties of a robust family of smooth ordinary differential equations exhibiting tangencies for a dense subset of parameters. We use this to find dense subsets of parameter values such that the set of solutions with historic behaviour contains an open set. This provides an affirmative answer to Taken's Last Problem (F. Takens (2008) Nonlinearity, 21(3) T33–T36). A limited solution with historic behaviour is one for which the time averages do not converge as time goes to infinity. Takens' problem asks for dynamical systems where historic behaviour occurs persistently for initial conditions in a set with positive Lebesgue measure. The family appears in the unfolding of a degenerate differential equation whose flow has an asymptotically stable heteroclinic cycle involving two-dimensional connections of non-trivial periodic solutions. We show that the degenerate problem also has historic behaviour, since for an open set of initial conditions starting near the cycle, the time averages approach the boundary of a polygon whose vertices depend on the centres of gravity of the periodic solutions and their Floquet multipliers. This is a joint work with I. Labouriau (University of Porto).

Alexandre A. Rodrigues
University of Porto
alexandre.rodrigues@fc.up.pt

MS32

Splitting of Separatrices at a Periodically Forced Hamiltonian-Hopf Bifurcation

Abstract Not Available At Time Of Publication.

Arturo Viero
University of Barcelona
vieiro@maia.ub.es

MS33

Noise-Induced Effects on Spontaneous and Spiral Wave Activity of the Biopacemaker

Spontaneous activity is the core of a normal heartbeat. The limitations in the natural hearts pacemaker can necessitate the implantation of an electronic pacemaker. The biological pacemaker approach has been proposed as a possible alternative with the creation of a new multicellular pacemaking substrate. Interaction between cell types is central to the function of this new approach. The present project focuses on studying the effect of current noise on spontaneous activity (focal and reentrant dynamics) of multicellular mixture of two different cell population, pacemaker and quiescent cardiac cells. Simulations were carried out in a 2D spatial cardiac model. Currents were represented by the Luo-Rudy I ionic model and a bias current that was introduced to induce spontaneous activity in pacemaker cells. Sensitivity to the current noise was simulated as a function of spontaneous activity of pacemaker cells for different stochastically distributed pacemaker cells patterns. The presence of noise lowered the minimum density of pacemaker cells needed for focal spontaneous activity. The effects of noise on spatial-temporal dynamics are more important with weak pacemaker cells. Sensitivity to reentrant activity highlights the synergetic interaction between pacemaker action potential morphology and the spatial pattern distribution. The project will provide a better understanding of noise interaction with initiation of spontaneous activity within the concept of biological pacemaker.

Alireza Aghighi
Institute of Biomedical Engineering
Université de Montréal
alireza.aghighi@umontreal.ca

Philippe Comtois
Institute of Biomedical Engineering,
Universite de Montreal

philippe.comtois@umontreal.ca

MS33

Semianalytical Approach to Criteria for Ignition of Excitation Waves

We consider the problem of ignition of propagating waves in one-dimensional bistable or excitable systems by an instantaneous spatially extended stimulus. Earlier we proposed a method (Idris and Biktashev, PRL, vol 101, 2008, 244101) for analytical description of the threshold conditions based on an approximation of the (center-)stable manifold of a certain critical solution. Here we generalize this method to address a wider class of excitable systems, such as multicomponent reaction-diffusion systems and systems with non-self-adjoint linearized operators, including systems with moving critical fronts and pulses. We also explore an extension of this method from a linear to a quadratic approximation of the (center-)stable manifold, resulting in some cases in a significant increase in accuracy. The applicability of the approach is demonstrated on five test problems ranging from archetypal examples such as the Zeldovich–Frank-Kamenetsky equation to near realistic examples such as the Beeler-Reuter model of cardiac excitation. While the method is analytical in nature, it is recognised that essential ingredients of the theory can be calculated explicitly only in exceptional cases, so we also describe methods suitable for calculating these ingredients numerically.

Burhan Bezekci
University of Exeter, Exeter, UK
b.bezekci@exeter.ac.uk

Ibrahim Idris
Bayero University, Kano, Nigeria
ibb.idris@gmail.com

Radostin Simitev
University of Glasgow, Glasgow, UK
radostin.simitev@glasgow.ac.uk

Vadim N. Biktashev
College of Engineering, Mathematics and Physical Sciences
University of Exeter
V.N.Biktashev@exeter.ac.uk

MS33

Local Heterogeneities in Cardiac Systems Suppress Turbulence by Generating Multi-Armed Rotors

Ventricular fibrillation is an extremely dangerous cardiac arrhythmia that is linked to rotating waves of electric activity and chaotically moving vortex lines. These filaments can pin to insulating, cylindrical heterogeneities which swiftly become the new rotation backbone of the local wave field. For thin cylinders, the stabilized rotation is sufficiently fast to repel the free segments of the turbulent filament tangle and annihilate them at the system boundaries. The resulting global wave pattern is periodic and highly ordered. Our cardiac simulations show that also thicker cylinders can establish analogous forms of tachycardia. This process occurs through the spontaneous formation of pinned multi-armed vortices. The observed number of wave arms N depends on the cylinder radius and is associated to stability windows that for $N = 2$, 3 partially overlap. We also discuss the effects of anisotropy caused by fiber rotation.

Oliver Steinbock
Department of Chemistry and Biochemistry
Florida State University
steinbck@chem.fsu.edu

Zhihui Zhang
Florida State University
zz11c@my.fsu.edu

MS33

Fractional-Order Voltage Dynamics Suppresses Alternans and Promotes Spontaneous Activity in a Minimal Cardiomyocyte Model

Electrical activity in cardiomyocytes is typically modeled using an ideal parallel resistor-capacitor circuit. However, studies have suggested that the passive properties of cell membranes may be more appropriately modeled with a non-ideal capacitor, in which the current-voltage relationship is given by a fractional-order derivative. Fractional-order membrane potential dynamics introduces capacitive memory effects, i.e., dynamics are influenced by the prior membrane potential history. We recently showed that fractional-order dynamics alter ionic currents and spiking rates in neurons. Here, we investigate fractional-order dynamics in a cardiomyocyte model using the 3-variable Fenton-Karma model. Simulations, performed for fractional-orders between 0.5 and 1 and variable cycle lengths, showed that the action potential duration (APD) was shortened as the fractional-order decreased, for all cycle lengths. At short cycle lengths at which APD alternans was present in the first-order model, alternans was suppressed. Finally, for small fractional-order, spontaneous action potentials followed pacing. Short-term memory effects were represented by a hypothetical memory current, which was primarily outward for fractional-order closer to 1, shortening APD, and primarily inward for fractional-order closer to 0.5, generating spontaneous action potentials. Collectively, our results suggest the capacitive memory may play a role in both alternans formation and pacemaking.

Tien Comlekoglu
Virginia Commonwealth University
comlekoglutn@mymail.vcu.edu

Seth Weinberg
Department of Biomedical Engineering
Virginia Commonwealth University
shweinberg@vcu.edu

MS34

Neural Synchronization During Neocortical Seizures

The question of the role of synchronization during seizures has been intensely debated both by the clinical and nonlinear dynamics community. We have investigated this in focal seizures in the rat neocortex. The seizures are induced by 4-aminopyridine, which blocks potassium channels. Seizure recording is obtained using a local field potential recording as well as imaging with a voltage-sensitive dye in order to record voltage changes throughout the affected area. We find a significant increase in synchronization during the seizure events, quantified using the stochastic phase synchronization index. In agreement with the experimental observations, the elimination of potassium con-

ductance in an array of simulated coupled neurons results in seizure-like mean field oscillations. More specifically, in the computational model, seizure initiation occurs as a bifurcation when the potassium conductance is varied as a control parameter. Our results suggest that experimentally observed changes in field potential amplitude and frequency during the course of a seizure may be explained by noise-induced transitions among multistable states.

Daisuke Takeshita
University of Helsinki
daisuke.takeshita@helsinki.fi

Sonya Bahar
Center for Neurodynamics and Dept. of Physics and Astronomy
University of Missouri at St. Louis
bahars@umsl.edu

MS34

Engineering Reaction-Diffusion Networks with Properties of Neural Tissue

We present an experimental system of networks of coupled non-linear chemical reactors, which we theoretically model within a reaction-diffusion framework. The networks consist of patterned arrays of diffusively coupled nanoliter-scale reactors containing the Belousov-Zhabotinsky (BZ) reaction. Microfluidic fabrication techniques are developed that provide the ability to vary the network topology, the reactor coupling strength and offer the freedom to choose whether an arbitrary reactor is inhibitory or excitatory coupled to its neighbor. This versatile experimental and theoretical framework can be used to create a wide variety of chemical networks. Here we design, construct and characterize chemical networks that achieve the complexity of central pattern generators, which are found in the autonomic nervous system of a variety of organisms. We envision that this artificial nervous system can serve as the controller of a synthetic musculature comprised of chemomechanical gels coupled to the BZ layer in order to create soft robots capable of autonomous activity.

Seth Fraden
Brandeis University
Department of Physics
fraden@brandeis.edu

Thomas Litschel
Brandeis University
Department of Biochemistry
tolitsch@brandeis.edu

Michael M. Norton
Brandeis University
Department of Physics
mmnorton@brandeis.edu

MS34

Partially Synchronized States in Small Networks of Electrochemical Oscillators: Effect of Heterogeneities and Network Topology

When electrochemical reactions take place on electrode arrays, a network can form through the potential drop among the elements. The goal of the presentation is to show how synchronization and network theories can be applied to describe the partially synchronized patterns of the oscillatory chemical reaction system. We consider two fundamental mechanisms for partially synchronized states. In oscillations close to Hopf bifurcation and nearly identical natural frequencies, we describe the emergence of chimera states. The experiments point out the importance of low level of heterogeneities (e.g., surface conditions) and optimal level of coupling strength and time-scale as necessary components for the realization of the chimera state. For systems with large heterogeneities, a remnant chimera state is identified where the pattern is strongly affected by the presence of frequency clusters. For experimental conditions where chimera states are not possible, we analyze the spatially organized partially synchronized states as a function of underlying heterogeneities and network topologies. As prototype system, we consider three oscillators with superimposed local and global coupling topologies. An approximate formula is derived for the mixed local/global coupling topology for the critical coupling strength at which full synchrony is achieved. The formula is verified with macrocells, in which the coupling topology is systematically varied from local to global coupling.

Istvan Z. Kiss
Department of Chemistry
Saint Louis University
izkiss@slu.edu

MS34

Order and Information Flow in an Array of Electronic Neurons

A small array of FitzHugh-Nagumo neurons was constructed. The nine neurons, connected in a ring with nearest neighbor coupling, exhibited either unsynchronized firing or synchronized behavior, depending on the coupling strength. However a new state, a *chimera*, appeared when a single long-distance link (*small world coupling*) was introduced.
It was possible to calculate the time-dependent behavior of the order parameter of the system. Of greater interest for understanding computation in such a system, we were also able to determine, via symbolic dynamics, the information flow in the system as a function of time, both with and without the small world link, and to relate it to the order parameter. This approach should be generally applicable to more complex arrays of electronic and biological neurons as well.

Mark Spano
School of Biological and Health Systems Engineering
Arizona State University
mark.spano@mac.com

Easwara Arumugam
Electrical Geodesics, Inc.
emoorthy@egi.com

MS35

Using Bistability, Oscillations and Slow-Fast Dynamics to Engineer Population Density Control and Stable Coexistence of Competitive Bacterial Strains

In order to safely and reliably translate more than a decade of research on engineered gene regulatory networks to medical or industrial settings, it is necessary to develop strategies to systematically control bacterial population dynamics. These strategies may be employed to limit growth as a safety precaution, to release intracellularly produced chemical compounds via lysis, or to co-culture different bacterial strains for multi-step industrial fermentation processes. Here, we use a reduced deterministic model to identify the design principles and theoretical limitations of a recently published self-lysis circuit [Din et al., Nature 563, 2016] that is based on diffusive signaling within the population and activates upon reaching a quorum threshold. We find that the conditions for the onset of population size oscillations derived from the model are consistent with experimentally observed behavior in microfluidics. Robust oscillations are driven by the bistability arising from a core positive feedback loop and their period can be experimentally tuned and analytically predicted in certain limits. Since the circuit makes population growth self-limiting, we also use the model to explore the possibility of co-culturing two strains that use different quorum sensing systems. Depending on the individual parameters and cross-talk between the quorum-sensing systems, we find distinct multi-strain dynamics that could be useful for a variety of applications.

Philip Bittihn
BioCircuits Institute
University of California, San Diego
pbittihn@ucsd.edu

MS35

Cooperation in Synthetic Bacterial Communities: Optimality, Fragility and Interaction Non-Additivity

Cooperation is one of the major social interactions that contribute to the spatiotemporal organization of bacterial communities, such as biofilms. Understanding its functional traits is important for characterizing, predicting and eventually engineering the dynamics of complex communities. Although bacterial cooperation has attracted considerable interest over the decades, what remains unsolved is how its key molecular traits contribute to the structural characteristics of a community. Using engineered Lactococcus lactis consortia as model systems, we have investigated how three key aspects of cooperationoptimality, fragility, and competition non-additivitycontribute to community organization. Our studies show that (10 optimality of cooperation is determined by the stoichiometric ratio of molecules engaged in cooperation, (2) that fragility of cooperation increases with the decrease of cell populations, and (3) that cooperation can revoke the additivity of competition in communities consisting of multiple species. Furthermore, we extended our exploration from well-mixed liquid settings to solid agar plates, under which heterogeneous spatial structures of communities emerged. This study yields new insight into bacterial cooperation, providing broad implications for understanding and engineering complex community structures including biofilms.

Ting Lu
University of Illinois
luting@illinois.edu

MS35

Excitable Toxin-Antitoxin Modules Coordinated Through Intracellular Bottlenecks

Chronic infections and pathogenic biofilms present a serious threat to the health of humans by decreasing life expectancy and quality. The resilience of these microbial communities has been attributed to the spontaneous formation of persister cells, which constitute a small fraction of the population capable of surviving a wide range of environmental stressors. Gating of bacterial persistence has recently been linked to toxin-antitoxin (TA) modules, which are operons with an evolutionarily conserved motif that includes a toxin that halts cell growth and a corresponding antitoxin that neutralizes the toxin. While many such modules have been identified and studied in a wide range of organisms, little consideration of the interactions between multiple modules within a single host has been made. Moreover, the multitude of different antitoxin species are degraded by a relatively small number of proteolytic pathways, strongly suggesting competition between antitoxins for degradation machinery, i.e. queueing coupling. Here we present a theoretical understanding of the dynamics of multiple TA modules that are coupled through either proteolytic queueing, a toxic effect on cell growth rate, or both. We conclude that indirect queueing coordination between multiple TA modules may be central to controlling bacterial persistence.

William H. Mather
Virginia Tech Physics
wmather@vt.edu

MS35

Dynamic Ligand Discrimination in the Notch Signaling Pathway

A mysterious aspect of Notch signaling, and many other developmental signaling pathways, is the use of distinct ligands in different developmental contexts despite their similar abilities to interact with receptors. With Notch in particular, because the pathway provides no known mechanism by which signal-receiving cells might discern the identity of an activating ligand, it has remained unclear whether, and how, cells could adopt distinct gene expression programs or cell fates in response to signaling by different ligands. Using quantitative single-cell imaging in cell-culture, we discovered that the Notch pathway uses dynamics to discriminate signaling by the closely related ligands Dll1 and Dll4 through a single receptor, Notch1. Dll1 activates Notch1 in discrete, frequency-modulated pulses that preferentially regulate the Notch target gene Hes1. By contrast, Dll4 activates Notch1 in a sustained, amplitude-modulated manner that up-regulates different direct targets such as Hey1/L.Mathematical modeling of the Hes/Hey circuit, including auto- and cross-repression between factors, reveals how Notch signaling dynamics can be decoded through an incoherent feed-forward architecture to activate distinct target genes. Taken together,these data show that the Notch pathway uses dynamics to effectively establish multiple channels of communication through a single receptor.

Sandy Nandagopal
California Institute of Technology
sandyn@caltech.edu

MS36

Traveling Waves in Fluids: Bifurcations with Respect to the Wave Speed

In this talk, I will present some new results on traveling waves in fluids. Two examples will be featured prominently: electromigration dispersion waves in a capillary and acoustic waves in thermoviscous perfect gases. In the former case, a reduction to Darboux's equation is obtained. In the latter case, an "elementary" nonlinear ODE (specifically, a special case of Abel's equation) is derived for inviscid but thermally conducting gases, while the case of viscous but non-thermally conducting gases leads to a more complicated nonlinear ODE. In all contexts, exact (but implicit) solutions are constructed for traveling waves (specifically, “kinks”) connecting distinct equilibria of their respective ODE. In both the case of electromigration dispersion waves and acoustic waves in viscous but non-thermally conducting gases, the governing ODE is shown to exhibit a transcritical bifurcation with respect to the dimensionless wave speed at the value of unity. I will conclude the talk by highlighting the generic nature of such transcritical bifurcations at unit wave speed in fluid mechanics.

Ivan C. Christov
Purdue University
christov@purdue.edu

MS36

Course-Grained Models for Interacting Flapping Swimmers

We present the results of a theoretical investigation into the dynamics of interacting flapping swimmers. Our study is motivated by ongoing experiments in the NYU Applied Math Lab, in which freely-translating, heaving airfoils interact hydrodynamically to choose their relative positions and velocities. We develop a discrete dynamical system in which flapping swimmers shed point vortices during each flapping cycle, which in turn exert forces on the swimmers. We present a framework for finding exact solutions to the evolution equations and for assessing their stability, which is nontrivial owing to the temporal nonlocality in the governing equations. Our analysis gives physical insight into the preference for certain observed ”schooling states.” Numerical simulation of the governing equations reveals that the swimmers may undergo a complex nonlinear dynamics while maintaining a bound state. The model may be extended to arrays of flapping swimmers, and configurations in which the swimmers’ flapping frequencies are incommensurate. Generally, our results indicate how hydrodynamics may mediate schooling and flocking behavior in biological contexts.

Anand Oza, Leif Ristroph
Courant Institute, NYU
oza@cims.nyu.edu, lr1090@nyu.edu

Michael J. Shelley
New York University
Courant Inst of Math Sciences
shelley@cims.nyu.edu

MS36

Bifurcations in Walking Droplet Dynamics

Bouncing droplets on a vibrating fluid bath can exhibit behavior analogous to wave-particle duality, such as being propelled by the waves they generate. These droplets seem to walk across the bath, and thus are dubbed *walkers*. Walkers can exhibit exotic dynamical behavior which give strong indications of chaos, but many of the interesting dynamical properties have yet to be proven. In a recent work by Gilet (PRE 2014) a discrete dynamical model is derived and studied numerically. We prove the existence of Neimark-Sacker bifurcations for a variety of eigenmode shapes of the waves and parameter regimes from this model. Then we reproduce numerical experiments done by Gilet and produce new numerical experiments and apply our theorem to the test functions used for that model in addition to new test functions. We also show evidence of a new class of bifurcation, which is discussed in more detail in Part II.

Aminur Rahman, Denis Blackmore
New Jersey Institute of Technology
ar276@njit.edu, denis.l.blackmore@njit.edu

MS36

The Annihilation of Periodic Points and Barriers to Transport by Discontinuous ‘Slip’ Deformations in a Fluid Flow

Fluid mixing and fluid particle transport has primarily been considered in smooth flows, driven by ‘stretching and folding’ motions. However, there exist a broad range of flows that admit discontinuous ‘slip’ deformations; including valved flows, granular flows and shear banding materials. In these systems mixing and particle transport can also be generated by ‘cutting and shuffling’ motions. We demonstrate the interplay between these discontinuous deformations and bifurcations of periodic points in a model fluid flow with valves. In particular, we show that discontinuous deformations destroy some Lagrangian structures associated with bifurcations, including barriers to fluid transport, while leaving other structures intact.

Lachlan Smith
Dept. of Chemical & Biological Engineering
Northwestern University
lachlan.smith@northwestern.edu

Murray Rudman
Monash University
murray.rudman@monash.edu

Daniel Lester
Dept. of Civil, Environmental & Chemical Engineering
RMIT
daniel.lester@rmit.edu.au

Guy Metcalfe
School of Mathematical Sciences
Monash University
guy.metcalfe@monash.edu

MS37

Realization of Nonlinear Resonances in Multiple Modes of a Microcantilever Polymer System

Advances in micro/nano-scale fabrication techniques have led the extensive development of microelectromechanical systems (MEMS). Among them, resonator-based MEMS designs often employ beam-type mechanical structures in micro/nanometer scales, designed to exhibit mechanical motion usually at their high resonant frequencies with high Q factors. Intentional implementation of geometric nonlinearity has suggested ways to break through the limitations of linear MEMS by utilizing beneficial nonlinear characteristics, not attainable in a linear setting. Integration of nonlinear couplings to an otherwise purely linear microcantilever is a promising way to intentionally realize geometric nonlinearity. Here, we demonstrate a nonlinear microresonator consisting of a silicon microcantilever and a polymer attachment exhibiting strong nonlinear hardening behavior not only in the first flexural mode but also in higher modes. In this design, we intentionally implement a drastic and reversed change in the axial vs. bending stiffness between the Si and polymer components by varying the geometric can material properties. By doing so, resonant oscillations induce large axial stretching within the polymer component, which effectively introduces geometric stiffness and damping nonlinearity. The efficacy of the design and the mechanism of geometric nonlinearity are confirmed through a comprehensive experimental, analytical, and numerical analysis on the nonlinear dynamics of this system.

Keivan Asadi
Dept. of Mechanical and Aerospace Engineering, The Ohio Sta
keivan.asadi@ttu.edu

Snehan Peshin, Junghoon Yeom
Dept. of Mechanical Engineering, Michigan State University,
peshinsn@msu.edu, jyeom@msu.edu

Hanna Cho
Ohio State University
cho.867@osu.edu

MS37

Energy Exchange in Strongly Nonlinear Systems: Canonical Formalism

Over recent years, a lot of progress has been achieved in understanding of the relationship between localization and transport of energy in essentially nonlinear oscillatory systems. In this paper we are going to demonstrate that the structure of the resonance manifold can be conveniently described in terms of canonical action-angle variables. Such formalism has important theoretical advantages: all resonance manifolds may be described at the same level of complexity, appearance of additional conservation laws on these manifolds is easily proven both in autonomous and non-autonomous settings. The harmonic balance - based complexification approach, used in many previous studies on the subject, is shown to be a particular case of the canonical formalism. Moreover, application of the canonic averaging allows treatment of much broader variety of dynamical models. As an example, energy exchanges in systems of coupled trigonometrical and vibro-impact oscillators are considered. Other examples address dynamics of forced vibro-impact oscillator and of Hamiltonian chain of such coupled oscillators.

Oleg Gendelman
Technion Israel Institute of Technology
ovgend@tx.technion.ac.il

Themistoklis Sapsis
Massachusetts Institute of Techonology
sapsis@mit.edu

MS37

High-amplitude Stationary Dynamics, Energy Transfer and Localization in Sine-lattice

The strongly nonlinear dynamics of the discrete model of the harmonically coupled pendula (Sine-lattice) is considered in a wide interval of oscillation amplitudes. The semi-inverse procedure is used for the derivation of the main asymptotic approximation, that allows to estimate the nonlinear normal modes' (NNMs) spectrum as well as to analyze the non-stationary resonance dynamics in terms of the limiting phase trajectories (LPTs). It was shown that the spectrum of the NNMs at the large amplitudes is specified by the non-monotonic dispersion curves that leads to the multitude of the resonances. The domains of the NNMs instability are found analytically in the framework of the developed approach. It was shown that the nonlinear resonant interaction of the long wavelength NNMs leads to the intensive energy exchange or energy localization in some domain of the lattice, which are described by the LPTs. The threshold corresponding to LPT instability (the transition to energy localization) is also estimated analytically. The numerical simulation of the large-amplitude dynamics of the finite model of the Sine-lattice confirms the conclusions of the asymptotic analysis with a good accuracy. The problem of chaotic regimes in the short discrete Sine-lattices is discussed.

Leonid Manevitch
Semenov Institute of Chemical Physics
Russian Academy of Sciences
manevitchleonid3@gmail.com

Valeriy Smirnov
N.N. Semenov Institute of Chemical Physics, RAS
vvs@polymer.chph.ras.ru

MS37

Resonance Energy Transfer Between Charged Particles and Electromagnetic Waves

In the present talk we review recent studies of multi-scale plasma systems where the nonlinear resonant interaction between charged particles and electromagnetic waves plays an important role; and discuss particular examples of the acceleration of charged particles by scattering on resonances and capture into resonance. We focus on a system, where both scattering and capture allow particles to investigate different domains of the phase space. We compute the effects of a single scattering and a single capture on adiabatic invariants, and show how these effects can be combined into a Fokker-Plank-type equation for the probability distribution function for an adiabatic invariant. We compute the rates of mixing and energy transport from the wave to the particles.

Dmitri Vainchtein
Drexel Plasma Institute
dlv36@drexel.edu

Anton Artemyev
Institute of Geophysics and Planetary Physics, UCLA
ante0226@yandex.ru

Fan Wu
Central South University, China
168162131@qq.com

MS38

Large Deviations in Stochastic Hybrid Networks

We construct a path-integral representation of solutions to a stochastic hybrid system or piecewise deterministic Markov process, consisting of one or more continuous variables evolving according to a piecewise-deterministic dynamics. The differential equations for the continuous variables are coupled to a set of discrete variables that satisfy a continuous-time Markov process, which means that the differential equations are only valid between jumps in the discrete variables. Examples of stochastic hybrid systems arise in biophysical models of stochastic ion channels, motor-driven intracellular transport, gene networks, and stochastic neural networks. We use the path-integral rep-

resentation to derive a large deviation action principle for a stochastic hybrid system, which can be used to solve first passage time problems. We also derive a Feynman-Kac formula for the residence time of a stochastic hybrid system.

Paul C. Bressloff
University of Utah
Department of Mathematics
bressloff@math.utah.edu

MS38

Can Finite Size Effects in Networks Be Represented by Stochastic Mean-Field Dynamics?

The complex dynamics of phase oscillator networks a received great attention in recent years. The thermodynamic limit with infinitely many nodes often allows for analytical treatment with the approach of Ott and Antonsen as most popular example [Ott, Antonsen, Chaos 18, 037113 (2008)]. In this talk the focus is on finite-size networks for which the analytic treatment is limited. For a fully connected, homogeneous network we start off with the Ott and Antonsen manifold that covers its mean-field or order parameter dynamics. By reducing network size stepwise we investigate to what extent the original low-dimensional order parameter dynamics stays in tact while erratic behavior emerges due to the random realization of the oscillators natural frequencies. For different network sizes we analyze numerically obtained time series of the order parameter using the Kramers-Moyal expansion. This expansion into corresponding conditional cumulants [Friedrich, Peinke. Physical Review Letters 78(5):863 (1997); Gradiek, Siegert, Friedrich, Grabec. Physical Review E 62(3A):3146 (2000)] yields so-called drift and diffusion coefficients that represent the deterministic and stochastic components of the dynamics, respectively. While the first largely resembles the dynamics in the thermodynamic limit presuming sufficiently large networks, the latter does support the idea that finite-size effects give rise to diffusion-like stochastic components in the mean-field dynamics.

Andreas Daffertshofer
MOVE Research Institute Amsterdam
VU University Amsterdam
a.daffertshofer@vu.nl

MS38

Noise-Induced Optimal Dynamics in Self-Organizing Adaptive Networks

Recent studies have shown that adaptive networks driven by simple local rules can organize into critical global steady states, providing another framework for self-organized criticality (SOC). In this talk, based upon the paper [C. Kuehn, Time-scale and noise optimality in self-organized critical adaptive networks, Phys. Rev. E 85, 026103, 2012], I shall focus on the important convergence to criticality and show that noise and time-scale optimality are reached at finite values. This is in sharp contrast to the previously believed optimal zero noise and infinite time-scale separation case. Furthermore, a noise-induced breakdown of SOC is observed. The noise-optimality effect can be understood particularly well using a simple conceptual model, which reveals a new version of stochastic resonance, which we call steady-state stochastic resonance.

Christian Kuehn
Technical University of Munich
ckuehn@ma.tum.de

MS38

Designing Noisy Networks

A heteroclinic network is a finite set of dynamical states connected by trajectories in phase space. Heteroclinic networks appear robustly in a range of applications and have been used as a way to model a number of types of biological and cognitive processes. Excitable networks are a close relation of heteroclinic networks for which finite amplitude perturbations are required to transition from one state to another. I will present methods for realizing an arbitrary directed graph as a heteroclinic or excitable network in phase space. These networks attractors display a high sensitivity to low amplitude noise both in terms of the regions of phase space visited and in terms of the sequence of the transitions around the network. In some circumstances, the noise may even cause long-time correlations, or memory, in the sequence of transitions between states. I will give some results that quantify the effect of noise on these attractors; specifically, how to characterize residence times at states and switching rates between states. I will also discuss several new applications of this work to modelling neural processes.

Claire M. Postlethwaite
University of Auckland
c.postlethwaite@auckland.ac.nz

Peter Ashwin
University of Exeter
p.ashwin@ex.ac.uk

MS39

Data Assimilation for Geophysical Fluids: Back and Forth Nudging (BFN) and Observers

The Back and Forth Nudging (BFN) algorithm is a prototype of a new class of data assimilation methods, although the standard nudging algorithm is known for a couple of decades. It consists in adding a feedback term in the model equations, measuring the difference between the observations and the corresponding space states. The idea is to apply the standard nudging algorithm to the backward (in time) nonlinear model in order to stabilize it. The BFN algorithm is an iterative sequence of forward and backward resolutions, all of them being performed with an additional nudging feedback term in the model equations. We also present the Diffusive Back and Forth Nudging (DBFN) algorithm, which is a natural extension of the BFN to some particular diffusive models. These nudging-based algorithms can be extended to more complex observers, with the aim of correcting non-observed variables, and improving the convergence of the algorithm and estimation of the model state, but also with the aim of identifying model parameters.

Didier Auroux
University of Nice, France
auroux@unice.fr

MS39

Forecast Sensitivity to Observations and Observation Impact for Data Assimilation Systems

A posteriori, it is possible to evaluate the accuracy of forecast skill in the data assimilation system. Using an adjoint

technique that can be either explicit or ensemble based, forecast skill can be traced back to the observations used in the past analysis, leading to quantitative evaluation of observation impact and sensitivity to forecast skill. Thus Forecast Sensitivity to Observations (FSO) is a diagnostic tool that complements traditional data denial of the observing system experiments. In this talk, we will evaluate FSO of the operational numerical weather prediction. By careful examination of the innovation, i.e., difference in model background and observations, we will assess the effect of observation and model biases on FSO.

Kayo Ide
University of Maryland, College Park
ide@umd.edu

MS39

Multilevel Monte Carlo Methods for Data Assimilation

For half a century computational scientists have been numerically simulating complex systems. Uncertainty is recently becoming a requisite consideration in complex applications which have been classically treated deterministically. This has led to an increasing interest in recent years in uncertainty quantification (UQ). Another recent trend is the explosion of available data. Bayesian inference provides a principled and well-defined approach to the integration of data into an a priori known distribution. The posterior distribution, however, is known only pointwise (possibly with an intractable likelihood) and up to a normalizing constant. Monte Carlo methods have been designed to sample such distributions, such as Markov chain Monte Carlo (MCMC) and sequential Monte Carlo (SMC) samplers. Recently, the multilevel Monte Carlo (MLMC) framework has been extended to some of these cases, so that approximation error can be optimally balanced with statistical sampling error, and ultimately the Bayesian inverse problem can be solved for the same asymptotic cost as solving the deterministic forward problem. This talk will concern the recent development of MLMC data assimilation methods, which combine dynamical systems with data in an online fashion. Examples are ML particle filters and ensemble Kalman filters.

Kody Law
Oak Ridge National Laboratory
kodylaw@gmail.com

MS39

The Bayesian Formulation and Well-posedness of Fractional Elliptic Inverse Problems

We study the inverse problem of recovering the order and the diffusion coefficient of an elliptic fractional partial differential equation from a finite number of noisy observations of the solution. We work in a Bayesian framework and show conditions under which the posterior distribution is given by a change of measure from the prior. Moreover, we show well-posedness of the inverse problem, in the sense that small perturbations of the observed solution lead to small Hellinger perturbations of the associated posterior measures. We thus provide a mathematical foundation to the Bayesian learning of the order – and other inputs – of fractional models.

Daniel Sanz-Alonso
University of Warwick
daniel_sanz-alonso1@brown.edu

MS40

The Role of Localization and Center-Surround Structure in Compressive Sensory Signal Processing

For successful preservation of sensory information across pathways with widely varying numbers of neurons, it is necessary for neuronal network architecture to facilitate efficient signal processing. The center-surround receptive field structure, ubiquitous in the visual system, is hypothesized to be evolutionarily advantageous in image processing tasks. We address the potential functional benefits and shortcomings of localization and center-surround receptive fields in the context of an integrate-and-fire neuronal network model. Based on the sparsity of natural scenes, we derive a compressive-sensing framework for input image reconstruction utilizing evoked neuronal firing rates. We investigate how the accuracy of input encoding depends on the network architecture, and demonstrate that center-surround antagonism facilitates marked improvements in natural scene processing beyond uniformly-random excitatory connectivity. However, for specific classes of images, we show that the center-surround structure may underlie common optical illusions. In the context of signal processing, we expect this work may suggest new sampling protocols useful for extending conventional compressive sensing theory.

Victor Barranca
Swarthmore College
vbarran1@swarthmore.edu

MS40

Modeling Within and Across Area Neuronal Variability in the Visual System

Shared variability among neurons (noise correlations) have been commonly observed in multiple cortical areas (Cohen and Kohn, 2011). Moreover, noise correlations are modulated by cognitive factors, such as task engagement and attention (Cohen and Maunsell, 2009; Doiron et al. 2016). While there is much discussion about the consequences of noise correlations on neuronal coding, there is a general lack of understanding of the circuit mechanisms that generate and modulate shared variability in the brain. Recently, simultaneous microelectrode array recordings from V1 and MT in behaving monkeys (Ruff and Cohen, 2016) suggest that attention not only decreases correlations within a cortical area (MT), but also increases correlations between cortical areas (V1 and MT). The differential modulation of between-areas and within-area noise correlations impose further constraints on circuit mechanisms for the generation and propagation of noise correlations. We develop a spiking neuron network with spatiotemporal dynamics that internally generates shared variability matching the low dimensional structure widely reported across cortex. This variability results from macroscopic chaos in population rates, which correlates neurons from the same recurrent network while decoupling them from feedforward inputs. Attention is modeled as depolarizing the inhibitory neuron population, which reduces the internally generated shared variability and allows the network to better track input signal.

Chengcheng Huang
New York University
huangc@pitt.edu

Douglas Ruff, Marlene Cohen, Brent Doiron
University of Pittsburgh
douglas.ruff@gmail.com, marlenercohen@gmail.com, brent.doiron@gmail.com

MS40

Spatial Variation of Spike Initiation Threshold in Large Active Dendritic Arbors

The integration of synaptic inputs in a neuron can be nonlinear not just at the axon, but also locally in the dendrites if they possess active voltage-gated ion channels. Such nonlinearities can lead to, for example, compartmentalized responses to inputs, with branches acting as individual nonlinear units in which dendritic spikes occur. In a straight cable, above- and below-threshold conditions are known to be separated by an unstable threshold or critical surface. Here we demonstrate methods that can be used to find the critical synaptic conductance leading to a threshold solution, and apply them to large, branched dendritic arbors with voltage-gated conductances. The methods allow efficient description as to how the critical threshold is affected by factors such as branching geometry, constrictions or varicosities, and spatial variation of conductance densities.

William Kath
Department of Applied Mathematics, Northwestern University
Department of Neurobiology, Northwestern University
kath@northwestern.edu

MS40

Distinct Roles of Interneurons in Hippocampal Network Oscillations

The functional role of interneurons in the generation of hippocampal oscillations remains to be elucidated. For interneurons recorded in mice hippocampal CA1 area, by using time-delayed mutual information, we characterize two subsets of interneurons whose firing activities share high mutual information with theta-band (4-12 Hz) and ripple-band (100-250 Hz) LFP signals, respectively. Information flow direction further suggests their unique contribution to theta and ripple oscillations. Finally, we discuss the limitation of Granger Causality analysis in this case as well as in general neuronal data analysis.

Songting Li
Courant Institute of Mathematical Sciences
New York University
songting@cims.nyu.edu

Douglas Zhou
Shanghai Jiao Tong University
zdz@sjtu.edu.cn

David Cai
Courant Institute for Mathematical Sciences, NYU
Shanghai Jiao-Tong University
cai@cims.nyu.edu

Jiamin Xu, Longnian Lin
East China Normal University
jimmy_0926@hotmail.com, lnlin@brain.ecnu.edu.cn

MS41

Qualitative Properties of Large Systems of Ordinary Differential Equations

Recent work on reservoir computing has brought to the forefront a new set questions about the typical behavior of large sets of ordinary differential equations with fixed structure and random variations within that structure. Examples include situations in which large blocks of linear constant coefficient subsystems that are coupled through nonlinearities of a fixed form. On one hand, such a structure can be used as a computationally efficient alternative to the kernel methods appearing in support vector machines. In another context, such models give rise to chaotic behavior whose underlying periodic solutions can be tuned to closely match a given pattern. In this talk we will present some specific examples illustrating these points, as well as parts of what may become a general theory.

Roger Brockett
Division of Engineering and Applied Sciences
Harvard University
brockett@hrl.harvard.edu

Daniel J. Gauthier
Duke University
gauthier.51@osu.edu

MS41

Reservoir Computing Using Autonomous Boolean Networks Realized on a Field-Programmable Gate Array

In its typical configuration, a reservoir computer requires a randomly connected network with 100s to 1,000s of nodes, which is challenging to realize experimentally. One approach is to use an autonomous time-delay Boolean network for the reservoir, which can be realized on a commercial device known as a field-programmable gate array (FPGA). This platform allows for typical node time scales of under a nanosecond, opening up the possibility of very high speed operation of the reservoir computer, along with flexible design rules for optimizing the reservoir dynamics. We will describe the performance characteristics of FPGA-based autonomous time-delays Boolean networks for various tasks, such as forecasting a chaotic time series, classifying written-digit images, and identifying simple spatial-temporal patterns. We gratefully acknowledge the financial support of the U.S. Army Research Office grant #W911NF-12-1-0099.

Daniel J. Gauthier
Duke University
gauthier.51@osu.edu

Daniel Canaday, Aaron Griffith
Ohio State University, Columbus, OH, USA
canaday.14@osu.edu, griffith.637@osu.edu

Nicholas Haynes
Department of Physics
Duke University
nickdavidhaynes@gmail.com

Otti D'Huys
Aston University, Birmingham, UK
o.dhuys@aston.ac.uk

MS41

Nonlinear Dynamics of Reservoir Computing and

Prediction

Reservoir computing algorithms use a general-purpose, neural-network dynamical system to perform machine learning tasks. This talk will focus on the tasks of predicting a chaotic time series whose dynamics are unknown, and of inferring unobserved state variables of a chaotic system from observed variables. In each case, the observed time series is input to the reservoir system, creating a coupled drive-response system. I will describe specific algorithms, and discuss how their success is related to the concept of generalized synchronization.

Brian R. Hunt
University of Maryland
bhunt@ipst.umd.edu

MS41

Predicting Spatial-Temporal Dynamics Using Reservoir Computers

We consider the problem of predicting the future time evolution of a spatiotemporally chaotic process purely from previous measurements of time series from that process (without knowledge of a model producing the time series). Examples will be presented showing that reservoir computing is an extremely useful approach to this general problem. Issues considered will include design choices for reservoir parameters, parallel implementation schemes for favorable scaling to very large systems, and whether, when the prediction time is exceeded, the reservoir output continues to reproduce the ergodic dynamical properties of the original process (i.e., does the reservoir give the process 'climate'). [Supported by ARO.]

Edward Ott
University of Maryland
Inst. for Research in Electronics and Applied Physics
edott@umd.edu

Jaideep Pathak
UMD
jpathak@umd.edu

Zhixin Lu
University of Maryland
zhixin.lu1988@gmail.com

Brian Hunt
UMD
bhunt@umd.edu

Michelle Girvan
University of Maryland
girvan@umd.edu

MS42

Dynamics of Ions Control Most Biological Systems

Biology occurs in ionic solutions that are both physical and biological plasmas. Dynamics of ions determines the properties of plasmas. Ion channels are proteins with a hole down their middle that conduct spherical charges like Na^+, K^+, Ca^{2+}, and Cl^-, with diameter about 0.2 nm through a narrow tunnel of fixed charge (doping) with diameter about 0.6 nm. Ion channels control dynamics of electric charge and current flow across membranes. Channels are as significant in biology as transistors are in computers: most of biology is controlled by channels. Ion channels are manipulated by powerful techniques of molecular biology in hundreds of laboratories. Atoms (and thus charges) can be substituted a few at a time. The location of every atom is known in favorable cases. **Ion channels are one of the few living systems of great importance whose natural biological function can be well described by a tractable set of dynamical equations.** Ion channels are studied by Poisson Drift Diffusion equations familiar in plasma and semiconductor physics called Poisson Nernst Planck or ***PNP*** in biology. My collaborators and I have (almost) derived relevant dynamics from stochastic differential equations. Dimensional reduction yields tractable inverse, variational, and forward problems. Dynamical models fit data with only a handful of parameters that do not change even when concentration boundary conditions change value by 10^7.

Bob Eisenberg
Department of Molecular Biophysics and Physiology
Rush University
beisenbe@rush.edu

MS42

The Steric Pnp-Ok Model

The Poisson-Nernst-Planck (PNP) theory is one of the most widely used analytical methods to describe electrokinetic phenomena for electrolytes. The model, however, considers isolated charges and thus is valid only for dilute ion concentrations. The key importance of concentrated electrolytes in applications has led to the development of the steric PNP model which accounts for ion-ion steric interactions. This model has been successfully applied to the study of transport in ion channels. In this study, I will consider the steric Poisson-Nernst-Planck (PNP) theory and in particular show that in certain cases, the model gives rise to singular solutions. I will present a high-order model in which solutions are smooth, and will show that the model gives rise to multiple solutions.

Nir Gavish
Department of Mathematics
Technion ITT
ngavish@tx.technion.ac.il

MS42

Energetic Variational Approaches in Transport of Ionic Particles

Transport of charged ions is central to almost all biological activities. Flows of ions produce signaling in the nervous system, initiation of contraction in muscle, coordinating the pumping of the heart and regulating the flow of water through kidney and intestine. Ion concentrations inside cells are controlled by ion channel proteins through the lipid membranes. In this talk, continuum models are derived from the energetic variational approach which include the coupling between the electrostatic forces, the hydrodynamics, diffusion and crowding (due to the finite size effects), in particular, temperature fields and various boundary conditions. The models provide basic understanding of some important properties of proteins, such as the ion selectivity and sensor mechanism.

Chun Liu
Department of Mathematics, Penn State University
University Park, PA 16802

cxl41@psu.edu

MS42

Individual Flux Study Via Steady-State Poisson-Nernst-Planck Systems: Effects from Boundary Conditions

We provide a detailed study for ionic flow through ion channels for the case with three ion species, two positively charged having the same valence and one negatively charged, and with zero permanent charge. Our focus is on the effects of boundary conditions on the ionic flow. Beyond the existence of solutions of the model problem, we are able to obtain explicit approximations of individual fluxes and the I-V relations, from which effects of boundary conditions on ionic flows are examined in a great detail. Critical potentials are identified and their roles in characterizing these effects are studied. Compared to ionic mixtures with two ion species, a number of new features for mixtures of three ion species arise. Numerical simulations are performed, and numerical results are consistent with our analytical ones.

Mingji Zhang
New Mexico Institute of Mining & Technology
mingji.zhang@nmt.edu

MS43

Sparse Sensor Placement for Multiscale Phenomena

Multiscale dynamics pose challenges in determining modal decompositions with physical meaning which can render sensor placement particularly difficult. Localized features in space or time may play a crucial role for the phenomenon of interest but may be insufficiently resolved due to their low energy contribution. We determine near-optimal spatial sensors in state space using empirical interpolation methods (EIM, discrete EIM) on low-rank dynamic mode decomposition (DMD) modes. Such empirical interpolative methods are commonly employed with proper orthogonal decompositions in model reduction. We extend this sensor placement approach to multiscale physics problems using multi-Resolution DMD or mrDMD [Kutz et al., 2015], a recursive application of DMD in the time-frequency domain that separates flow features occurring at different timescales. The discovered sensors achieve accurate flow state reconstruction in representative multiscale examples including global ocean temperature data with an energetic El Niño mode. Interestingly, this method places sensors near coastlines without imposing additional constraints, which is beneficial from an engineering perspective.

Krithika Manohar
University of Washington
Dept of Applied Mathematics
kmanohar@uw.edu

Eurika Kaiser, Steven Brunton
University of Washington
eurika@uw.edu, sbrunton@uw.edu

Nathan Kutz
University of Washington
Dept of Applied Mathematics
kutz@uw.edu

MS43

The Data Mining of Sloppiness: Parameter Reduction for Complex Dynamical Systems

In the past decades, extensive effort has been expended on reducing the number of variables in large, complex dynamic models to obtain effective models of smaller dimension. Nevertheless, the concomitant reduction in the number of parameters dictating system response is a relatively recent endeavor. This area is classically covered by sensitivity analysis, which is nevertheless plagued by the fact that it is local and linear in nature. Sloppiness and active subspaces are two promising current directions, but a complete understanding and an effective algorithmic implementation of parameter reduction is still largely lacking. In this talk, we will explore the link between nonlinear data mining and parameter reduction by identifying and analyzing sets of effective parameters and possible parameterizations. Combining equation–free principles with machine learning algorithms, we propose a data–based approach to resolve "sloppy' parameter directions in both singularly– and regularly–perturbed kinetic models. Using that framework, we fully analyze the paradigmatic Michaeli–Menten–Henri mechanism, connect our results to a singular perturbation analysis and identify the number and nature of effective parameters in that system.

Antonios Zagaris
Wageningen UR
Central Veterinary Institute
antonios.zagaris@wur.nl

Ioannis Kevrekidis
Dept. of Chemical Engineering
Princeton University
yannis@princeton.edu

William Holiday
Princeton University
holiday@princeton.edu

MS43

Kernel Analog Forecasting and Its Applications

Analog forecasting is a nonparametric technique introduced by Lorenz in 1969 which predicts the evolution of observables of dynamical systems by following the evolution of samples in a historical record of observations of the system which most closely resemble the observations at forecast initialization. We discuss a family of forecasting methods which improve traditional analog forecasting by combining ideas from kernel methods for machine learning and state-space reconstruction for dynamical systems. A key ingredient of our approach is to replace single-analog forecasting with weighted ensembles of analogs constructed using local similarity kernels. The kernels used here employ a number of dynamics-dependent features designed to improve forecast skill, including Takens' delay-coordinate maps (to recover information in the initial data lost through partial observations) and a directional dependence on the dynamical vector field generating the data. We illustrate these techniques in atmosphere ocean science applications.

Zhizhen Zhao
University of Illinois

zhizhenz@illinois.edu

MS44

Introducing Topographical Influences in the Extended-Klausmeier Vegetation Model

Today, an increasing amount of vegetation patterns in semi-arid climates face the dangers of desertification. To understand the driving mechanics behind this effect many ecosystem models have been created over the last years - both very simplistic ones and very realistic ones. The current consensus indicates the importance of water availability for the survivability (and movement) of vegetation. In turn the water availability is greatly influenced by the topography. Often, simple models ignore the topographical details whereas advanced models can only be studied by means of numerical PDE simulations. In this talk, we present one way to add topographical effects in a simplified ecosystem model (extended-Klausmeier) that results in a heterogeneous PDE that we can still study analytically for some cases. Specifically we study the topographical effects on localized vegetation pulses, i.e. one-dimensional patches. This leads to new observations, including pulses that move downhill.

Robbin Bastiaansen
Mathematical Institute
Leiden University
r.bastiaansen@math.leidenuniv.nl

Arjen Doelman
Mathematisch Instituut
doelman@math.leidenuniv.nl

Martina Chirilus-Bruckner
University of Leiden
Mathematical Institute
m.chirilus-bruckner@math.leidenuniv.nl

MS44

Topographic Controls on Vegetation Patterns

Regular and irregular spatial patterns of vegetation have been observed in arid and semi-arid landscapes worldwide. Such patterns are the result of both endogenous and exogenous effects, the former pertaining to the intrinsic properties of the self-organization process, the latter reflecting spatial heterogeneities in soil properties and topographic features. In particular, topographic heterogeneities of the landscape can affect water runoff, infiltration, solar radiation and erosion processes, ultimately changing the spatial redistribution of resources and thus the pattern formation mechanism. While these landform-water-vegetation interactions have been largely recognized, they are often neglected in many vegetation pattern formation models, which have mainly focused on flat terrains or uniform slope profiles. Here we analyze the effects of accounting for landscape topographic features in models describing vegetation patchiness in water-limited systems. The influence of variations in local exogenous features such as topographic slope and aspect on pattern formation will be investigated.

Sara Bonetti, Amilcare Porporato
Duke University
sara.bonetti@duke.edu, amilcare.porporato@duke.edu

MS44

How Does Topography Impact Vegetation Patterns?

In many semi-arid ecosystems, vegetation forms spatial patterns in an apparent response to water scarcity. Using hypotheses for vegetation-water interaction, water transport, and vegetation spread, PDE models can generate comparable patterns via a self-organizing mechanism. These models are often analyzed assuming a uniformly sloped landscape with homogeneous water availability. Using satellite imagery and remote sensing of topography, we can examine predictions of the models, including a predicted relationship between slope and pattern wavelength. This relationship appears to be weak, perhaps because topography has a strong influence on water availability and transport over long length scales not included in the models. Identifying how topography impacts vegetation patterns may lead to a new generation of models for this system.

Sarah Iams
Harvard University
Cambridge, MA
siams@seas.harvard.edu

Andrew J. Bernoff
Harvey Mudd College
Department of Mathematics
ajb@hmc.edu

Karna V. Gowda
Northwestern University
karna.gowda@u.northwestern.edu

Chad M. Topaz
Dept. of Mathematics, Statistics, and Computer Science
Macalester College
ctopaz@macalester.edu

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

MS44

Topography and Water Transport in Semi-Arid Ecosystems

Abstract Not Available At Time Of Publication.

Amilcare Porporato
Duke University
amilcare.porporato@duke.edu

MS45

The Geometry of Blenders in a Three-dimensional Hénon-like Family

Blenders are a geometric tool to construct complicated dynamics in diffeomorphisms of dimension at least three and vector fields of dimension at least four. They admit invariant manifolds that behave like geometric objects which have dimensions higher than expected from the manifolds themselves. We consider an explicit family of three-dimensional Hénon-like maps that exhibit blenders in a specific regime in parameter space. Using advanced numerical techniques we compute stable and unstable manifolds in this system, enabling us to show one of the first numerical pictures of the geometry of blenders. We furthermore present numerical evidence suggesting that the regime of

existence of the blenders extends to a larger region in parameter space.

Stefanie Hittmeyer, Bernd Krauskopf, Hinke M. Osinga
University of Auckland
Department of Mathematics
stefanie.hittmeyer@auckland.ac.nz,
b.krauskopf@auckland.ac.nz, H.M.Osinga@auckland.ac.nz

Katsutoshi Shinohara
Hitotsubashi University
Graduate School of Commerce and Management
ka.shinohara@r.hit-u.ac.jp

MS45

Bifurcations of Degenerate Singular Cycles

We investigate the dynamics near a so-called singular cycle – a heteroclinic cycle involving a hyperbolic equilibrium point E and a hyperbolic periodic solution P, such that the connection from E to P is of codimension one and the connection from P to E occurs at a quadratic tangency (also of codimension one). We study such a cycle as the organizing center of a two-parameter bifurcation scenario. Depending on properties of the transition maps, we find different types of shift dynamics near the cycle. Breaking one or both of the connections we further explore the bifurcation diagrams previously begun by other authors. In particular, we identify multipulse homoclinic solutions to E and P as well as multipulse heteroclinic tangencies from P to E, and bifurcating periodic solutions.

Alexander Lohse
University of Hamburg
alexander.lohse@math.uni-hamburg.de

Alexandre A. Rodrigues
University of Porto
alexandre.rodrigues@fc.up.pt

MS45

Birth of Discrete Lorenz Attractors in Homoclinic and Heteroclinic Tangencies

A presence of non-transversal homoclinic or heteroclinic orbits (tangencies) in a dynamical system is regarded as a universal criterion of existence of a complex dynamics. However, it does not immediately lead to the emergence of genuine strange attractors (those preserving their strangeness under small perturbations) such as the Lorenz attractors. A list of three-dimensional diffeomorphisms with quadratic tangencies will be presented in which discrete Lorenz attractors are born in bifurcations. For some of them a stronger result was proved: in any neighbourhood there exist residual sets in which systems possess a countable number of coexisting discrete Lorenz attractors. To get Lorenz attractors one needs to have the effective dimension of the problem to be at least three. This means that there should be no global contraction/expansion and no global center manifolds. To fulfill the first condition the Jacobian at the saddle should be close to 1 in the homoclinic case, and in the heteroclinic case it is enough to have the contracting-expanding configuration, when the Jacobian at one saddle is less than one and greater than one at another saddle. The following conditions prevent the appearance of center manifolds: 1. At least one of the saddle fixed point is a saddlefocus; 2. All the fixed points are saddles but one of the homoclinic/heteroclinic orbits is non-simple; 3. A saddle is resonant (two stable eigenvalues either coincide or have opposite signs).

Ivan Ovsyannikov
University of Bremen, Germany
Ivan.I.Ovsyannikov@gmail.com

MS45

Complex Dynamics of Robust Pulse Generators in Reaction-Diffusion Systems

Heterogeneity is one of the most important and ubiquitous types of external perturbations. We study a spontaneous pulse-generating mechanism in an excitable medium with jump-type heterogeneity. Such a pulse generator (PG) has attracted considerable interest due to the computational potential of pulse waves in physiological signal processing. Exploring the global bifurcation structure of PGs as periodic solutions, we find firstly the conditions under which they emerge, i.e., the onset of PGs, secondly a candidate for the organizing center producing a variety of PGs. We devise numerical frameworks to trace the long-term behavior of PGs as periodic solutions, and we detect the associated terminal homoclinic orbits that are homoclinic to a special type of heterogeneity-induced ordered pattern with a hyperbolic saddle. [Yadome, M., Nishiura, Y. and Teramoto, T., SIAM Journal on Applied Dynamical Systems 13 (2014), 1168, 34 pages.]

Takashi Teramoto
Asahikawa Medical University
teramoto@asahikawa-med.ac.jp

MS46

Rescuing Pulsatile Insulin Secretion by Wiggling Glucose

Pancreatic islets manage elevations in the blood glucose level by secreting insulin into the bloodstream in a pulsatile or oscillatory manner. In this presentation, we show that although islet oscillations are lost by fixing the glucose stimulus at a high level, they may be rescued by subsequently converting the glucose stimulus to a sinusoidal wave. We predict that the ability of this wave to rescue oscillations should depend on the amplitude and frequency of the wave, using insights from an analysis of the dynamical system. This prediction is confirmed in experiments that employ a specially-designed microfluidics device. Our results suggest a mechanism whereby oscillatory blood glucose levels recruit non-oscillating islets to enhance pulsatile insulin output from the pancreas. They also provide support for the main hypothesis of the Dual Oscillator Model, that a glycolytic oscillator endogenous to islet β-cells drives pulsatile insulin secretion.

Richard Bertram, Joseph Mckenna
Department of Mathematics
Florida State University
bertram@math.fsu.edu, jmckenna@math.fsu.edu

Raghuram Dumpa
Florida State University
rdhumpa@gmail.com

Nikita Mukhitov
Department of Chemistry and Biochemistry
Florida State University
nmukhitov@chem.fsu.edu

Michael Roper

Florida State University
roper@chemmail.chem.fsu.edu

MS46

Centre Manifold Deformation in Impaired Ultradian Oscillations of Glucose Regulation

The accurate regulation and metabolisation of glucose is essential for releasing the energy essential for the proper functioning of cells and organs. This regulation operates in a cyclic way, as a result of a feedback loop in which phasic insulin release has a crucial role. In this contribution, we evaluate the effect of various physiological parameters on the production of the ultradian oscillatory regime in a nonlinear system comprising two delays. The system, based on the model introduced in [Li, Kuang, Mason, Modeling the glucoseinsulin regulatory system and ultradian insulin secretory oscillations with two explicit time delays, Jour Theor Biol,2006], takes into account both instantaneous and delayed insulin responses which, together with the hepatic glucose production, have an effect in generating the ultradian regime. It is analysed to show the effect of reduced insulin production or sensitivity on the oscillations and several strategies for reinstating its accuracy are described through Hopf bifurcation techniques. An analytical description is performed by approximating the centre manifold through the perturbation of periodic solutions. The resulting expressions provide a rational link between all the physiological parameters and the amplitude and frequency of the periodic solutions. This allows to quantify the contribution of the insulin sensitivity to the oscillatory regime and hence provide a basis for inverse problems aiming at measuring diabetic parameters.

Benoit Huard
Northumbria University
Department of Mathematics, Physics & Electrical Engineering
benoit.huard@northumbria.ac.uk

Maia Angelova, Adam Bridgewater
Department of Mathematics and Information Sciences
Northumbria University
maia.angelova@northumbria.ac.uk,
adam.bridgewater@northumbria.ac.uk

MS46

An Integrated System Towards Artificial Pancreas and its Numerical Trials

Millions of Americans suffer type 1 diabetes mellitus (T1DM) that is caused by the lack of insulin producing pancreatic beta-cells. Exogenous insulin or its analogues must be daily administered to utilize and lower the chronic high glucose level, ideally, though an artificial pancreas, an integrated system consisting of an insulin pump, a glucose monitoring system, and closed loop control (CLC) algorithms. An effective CLC algorithm is still lacking in handling the delayed effects of insulin in delivery mechanisms, GMS and the hepatic glucose production (HGP). The timing discrepancies and dose inaccuracies often cause undesired glucose fluctuations including both hyperglycemia and dangerous hypoglycemia. Our ultimate goal is to formulate an integrated system, consisting of several dynamical system models, with the aims to develop and validate effective CLC algorithms for artificial pancreas.

Jiaxu Li
University of Louisville
Department of Mathematics
jiaxu.li@louisville.edu

MS46

Information Transfer in Gonadotropin-Releasing Hormone (gnrh) Sensing and Signalling

Biochemical cell signalling networks are noisy communication channels; transmitting biological information and allowing cells to respond appropriately to external cues. In the context of reproductive endocrinology, cell signalling networks allow pituitary gonadotropes to sense pulses of Gonadotropin-releasing hormone (GnRH) and regulate the production of hormones (luteinizing hormone, LH; and follicle-stimulation hormone, FSH) which control reproduction. Here, we develop and study a simplified mathematical model of GnRH signalling in gonadotropes. Using the model we explore the systems sensitivity to GnRH dynamics; showing that the system is robust to changes in pulse width and concentration but sensitive to changes in pulse frequency. The model also reveals the interplay between fast (minute) and slow (minute-hour) negative feedback loops with maximal information transfer achieved at intermediate feedback levels. Consistent with this, experiments revealed that reducing or increasing negative feedback reduced information transfer in the system.

Margaritis Voliotis
University of Exeter
College of Engineering, Mathematics and Physical Sciences
m.voliotis@exeter.ac.uk

Krasimira Tsaneva-Atanasova
University of Exeter
k.tsaneva-atanasova@exeter.ac.uk

Craig McArdle
Laboratories for Integrative Neuroscience and Endocrinology,
University of Bristol
craig.mcardle@bristol.ac.uk

Amitesh Pratap, Kathryn Garner
University of Bristol
amitesh.pratap@ bristol.ac.uk, k.garner@bristol.ac.uk

MS47

Nonlinear Energy Transfers and Intermittent Energy Dissipation in Forced Shear Flows

It is believed that the intermittent fluctuations in turbulent shear flows are triggered by the energy transfer to the mean flow via nonlinear inertial interactions. However, because of the vast range of active spatial and temporal scales, identifying the responsible interactions is not straightforward. We show that the responsible modes can be formulated as the (initially unknown) solutions of an appropriate constrained variational problem. The variational problem can be solved at a low computational cost, and the solution is the nontrivial mode with instantaneously maximal transfer of energy to the mean flow. We demonstrate the application of this variational method on a direct numerical simulation of the two-dimensional Kolmogorov flow.

Mohammad Farazmand
School of Physics
Georgia Institute of Technology
mfaraz@mit.edu

Themistoklis Sapsis
Massachusetts Institute of Techonology
sapsis@mit.edu

MS47

Statistics of Spatially-Periodic Turbulence Driven by Steady Forces

We conduct direct numerical simulations of turbulence sustained by steady spatially-periodic forces under periodic boundary conditions in three directions. One of the most remarkable features of this system is that turbulence statistics (e.g. the energy dissipation rate) evolve quasi-periodically in time even at high Reynolds numbers. The periodicity implies a quasi-periodic sustaining process of the turbulence and is explained in term of turbulent energy cascade events. Another interesting feature is the following: when the forcing is sinusoidal with the wave number equal to unity, i.e. when the flow is the three-dimensional Kolmogorov flow, the steady laminar solution is linearly stable and the onset of turbulence is due to a sub-critical transition. We verify that the probability of the survival of the transient turbulence is an exponential function of the time in a low-Reynolds-number range. This feature was previously demonstrated by Linkmann and Morozov (2015) with another forcing. It seems that such a behavior is universal not only in the wall-bounded turbulence but also in turbulence without walls. We also found edge states between the steady flow and the transient turbulence, which might give useful information to understand the onset of turbulence in this simple system.

Susumu Goto
Osaka University
goto@me.es.osaka-u.ac.jp

Lennaert van Veen
UOIT
lennaert.vanveen@uoit.ca

MS47

Localized Turbulence in 2D Kolmogorov Flows

Spatially-localized turbulent states are mainly observed in subcritical wall turbulence such as pipe flow and Couette flow. We, however, have found localized turbulent states can be isolated also in two-dimensional Kolmogorov flow which is governed by the Navier-Stokes equations with a steady sinusoidal forcing in a doubly-periodic box. We will explain the roll of the flow rate in isolating a localized state and controlling their motions and interactions. Random and/or coherent movements of the center of a localized turbulent state are studied from the dynamical systems point of view. For example, for moderate values of Reynolds number and the flow rate, a localized turbulent state moves with a constant speed on average and changes its own direction randomly and intermittently. These intermittent changes of the direction can be understood as transfer processes among several chaotic attracting sets.

Yoshiki Hiruta
Gruduate School of Science
Kyoto University
hiruta@kyoryu.scphys.kyoto-u.ac.jp

Sadayoshi Toh
Kyoto University
toh@scphys.kyoto-u.ac.jp

MS47

Recurrent Flow Analysis in Kolmogorov Flows

Flows over periodic domains which are body forced in one direction by a steady, trigonometric function of large, monochromatic wavelength are typically called ‘Kolmogorov flows’ after Kolmogorov’s (1959) suggestion of a 2D version as a simple situation in which to study linear instability. Due to the absence of physical (non-slip) boundaries, the flow can be efficiently simulated using spectral methods. These simulations indicate that the flow undergoes a sequence of bifurcations as the forcing amplitude increases which quickly give way to complex dynamics. In this talk I’ll discuss work carried out to probe these complex dynamics using a recurrent flow analysis. The fruits of this analysis can be used to a posteriori predict certain statistics of the dynamics using periodic orbit theory (Chandler & Kerswell, *J. Fluid Mech.* **722**, 554, 2013, Lucas & Kerswell, *Phys. Fluids*, **27**, 045106, 2015) and uncover key dynamical processes of the flows (Lucas & Kerswell, arxiv:1611.04829).

Dan Lucas
DAMTP
Cambridge University
dl549@cam.ac.uk

Gary Chandler, Rich Kerswell
Department of Mathematics
University of Bristol, U.K.
g.j.chandler@bris.ac.uk, r.r.kerswell@bris.ac.uk

MS48

Can Inducible Resistance in Plants Cause Herbivore Aggregations? Spatial Patterns in an Inducible Plant/Herbivore Model

Many theories regarding the evolution of inducible resistance have an implicit spatial component, but most relevant population dynamic studies ignore spatial dynamics. We examined a spatially explicit model of plant inducible resistance and herbivore population dynamics to explore how these influence spatial patterning. Both transient and persistent spatial patterns developed in all models examined, where patterns manifested as wave-like aggregations of herbivores and variation in induction levels. Patterns arose when herbivores moved away from highly induced plants, there was a lag between damage and deployment of induced resistance, and the relationship between herbivore density and strength of the induction response had a sigmoid shape. These mechanisms influenced pattern formation regardless of the assumed functional relationship between resistance and herbivore recruitment and mortality. In models where induction affected herbivore mortality, large-scale herbivore population cycles driven by the mortality response often co-occurred with smaller scale spatial patterns driven by herbivore movement. When the mortality effect dominated, spatial pattern formation was completely replaced by spatially synchronized herbivore population cycles. Our results present a new type of ecological pattern formation driven by induced trait variation, consumer behavior, and time delays that has broad implications for the community and evolutionary ecology of plant defenses.

Kurt Anderson
University of California Riverside

Department of Biology
kurt.anderson@ucr.edu

Brian Inouye
Florida State University
Biology Department
bdinouye@bio.fsu.edu

Nora Underwood
Florida State University
nunderwood@bio.fsu.edu

MS48

Mathematical Models of RNA Interference in Plants

In this talk I will discuss a model of plant immune response with a special emphasis on the role of time delays representing maturation time of proliferating tissue and the activation delay of RNA interference. Detailed bifurcation analysis of this model will demonstrate how stability and dynamical behaviour is affected by the system parameters and the time delays [G. Neofytou, Y.N. Kyrychko, K.B. Blyuss, Time-delayed model of immune response in plants, *J. Theor Biol.* **389**, 28-39 (2016)]. I will also show how RNA interference can mediate interactions between two viruses in the same plant host, allowing for both cross-protection and cross-enhancement between viruses [G. Neofytou, Y.N. Kyrychko, K.B. Blyuss, Mathematical model of plant-virus interactions mediated by RNA interference, *J. Theor Biol.* **403**, 129-142 (2016).]

Konstantin Blyuss
Department of Mathematics
University of Sussex
k.blyuss@sussex.ac.uk

MS48

Exploring Fitness Effects of Plant Defenses Against Insect Herbivores

When attacked by insect herbivores, plants emit volatile chemicals. These chemicals are known to induce local defenses, prime neighboring plants for defense, and attract predators and parasitoids to combat the herbivores but are coupled with fitness costs. We examine the interactions between the model plant goldenrod and one of its insect herbivores, Trirhabda virgata, in order to explore how plant defense strategies influence both mean fitness of a field of goldenrod as well as spatial variation in plant fitness within the field.

Karen M. Cumings, Peter R. Kramer
Rensselaer Polytechnic Institute
Department of Mathematical Sciences
cumink@rpi.edu, kramep@rpi.edu

Bradford C. Lister
Rensselaer Polytechnic Institute
Department of Biological Sciences
listeb@rpi.edu

MS48

Plant Compensatory Regrowth and Plant Resistance Effects on the Population Dynamics of Herbivores and Plants

Herbivore outbreaks, where herbivore densities fluctuate by orders of magnitude, can be detrimental to natural and agricultural systems, but the mechanisms driving these outbreaks is unclear. Proposed bottom-up mechanisms focus on plant responses to herbivory, such as (1) resistance, where plants produce defensive chemicals that reduce herbivore survival, and (2) compensatory regrowth, where plants replace consumed biomass and increase the food available to the herbivore. To quantify their influence on population dynamics, we analyze discrete-time plant-herbivore models that incorporate these two plant responses. When plants return to carrying capacity each year, such as in agricultural systems, resistance does not produce outbreaks, but compensatory regrowth produces outbreaks only when plants overcompensate for herbivory by producing more biomass than was consumed. In systems with both plant responses, compensatory regrowth can dampen outbreaks at high levels of induced resistance and produce outbreaks at low levels of induced resistance. When plant population sizes can vary across years, such as in natural systems, plant responses can also cause herbivore outbreaks that consist of periods of low herbivore density followed by high density peaks. Effectively using plant responses in natural and agricultural systems requires understanding these interactions between plants and herbivores to mitigate as opposed to exacerbate pest problems.

Christopher Stieha
Department of Biology
Case Western Reserve University
cxs521@case.edu

Brian Lerch
Case Western Reserve University
bal88@case.edu

Katja Poveda
Cornell University
kap235@cornell.edu

Karen Abbott
Case Western Reserve University
kcabbott@case.edu

MS49

Analysis of New Walking Droplet Bifurcations

Gillet developed a planar, 2-parameter, smooth discrete dynamical system model for walking droplet motion of the form

$$f_{C,\mu} : \mathbf{R}^2 \to \mathbf{R}^2,$$

where $0 < C, \mu < 1$. This map exhibits exotic, apparently new types of bifurcations involving chaotic strange attractors as each parameter increases. The bifurcations, which are generated by interactions between an invariant closed Jordan curve and a stable manifold of a saddle point, are abstracted, analyzed in detail and extended to higher dimensions.

Denis Blackmore
New Jersey Institute of Technology
Newark, NJ 07102, USA
deblac@m.njit.edu

Aminur Rahman
New Jersey Institute of Technology

ar276@njit.edu

MS49

Topological Bifurcations of Vorticity

Vortices are the most important coherent structures in fluid dynamics. A simple way to keep track of the dynamics of vortices in 2D is to follow the motion of the critical points of the vorticity as they evolve in time. Vortex creation and destruction can be described as bifurcations of these points with time as the primary bifurcation parameter. We will discuss general equations of motion of the critical points obtained from the Navier-Stokes equations, and also consider some specific flows: The creation of the Karman vortex street behind a circular cylinder after the Hopf bifurcation, and vortex merging between between two initially Gaussian vortices in the core growth model.

Morten Brons
Tech University of Denmark
Department of Mathematics
mobr@dtu.dk

Morten Andersen, Jesper Schmidt Hansen
Department of Science and Environment
Roskilde University
moan@ruc.dk, jesperschmidthansen@gmail.com

Matthias Heil
School of Mathematics
The University of Manchester
m.heil@maths.man.ac.uk

MS49

Surprisingly Persistent Structures Predicted by Piecewise Isometries

While chaotic advection has long been studied, mixing by cutting and shuffling, a different mixing mechanism, is relatively unexplored and imperfectly understood. Unlike chaotic advection, cutting and shuffling maps do not stretch, possess no positive Lyapunov exponents, and exhibit no chaotic behavior in the usual sense. Yet they can mix quite effectively. Cutting and shuffling can be described in terms of the mathematical formalism of Piecewise Isometries (PWIs) in which an object is divided into a finite number of pieces which are rearranged back into the object's original shape. The trajectories of the cuts in the limit of infinite iterations forms the exceptional set, akin to a stroboscopic map. The complement of the exceptional set comprises non-mixing regions, similar to regular islands of typical chaotic systems. We apply PWIs to a hemispherical shell as a zeroth order model of mixing a spherical tumbler half-filled with particles and rotated alternately by $\leq 90^\circ$ about two axes. Non-mixing regions in the PWI correspond to surprisingly persistent non-mixing elliptic regions and global barriers to mixing occur, both similar to structures in experiments (X-ray visualization of a granular flow) and simulations using a continuum model. This merging of PWIs, dynamical systems, and physical applications suggests a novel paradigm for mixing that it is especially well suited to the study of granular materials. Funded by NSF Grant CMMI-1435065.

Richard M. Lueptow
Northwestern University
Department of Mechanical Engineering
r-lueptow@northwestern.edu

Paul Park
Northwestern University
paul-park@northwestern.edu

Zafir Zaman, Mengqi Yu
Northwestern University
Evanston, IL
zafirzaman2015@u.northwestern.edu,
mengqiyu2014@u.northwestern.edu

Paul Umbanhowar
Northwestern University
Evanston, IL 60208-3109
umbanhowar@northwestern.edu

Julio M. Ottino
Northwestern University
jm-ottino@northwestern.edu

MS49

Bifurcations in a Soft Billiard

Billiard dymaical systems have played a foundational role in statistical mechanics and dynamical systems theory due to their clean definition, rich dynamics and direct application to many problems in physics. In traditional billiard models a point particle moves force-free along a geodesic line and specularly reflects from a hard boundary. The new wrinkle here is a soft boundary. If the boundary is soft, then the particle will exchange energy with its environment on a scale that fits the definition of a small system, which puts this soft mechanical nonequilibrium system into the same thermodynamic category as molecular motors and large molecules such as DNA or proteins. Experiments on a soft triangular billiard can measure the probability distribution function of particle position, from which one can calculate the information entropy as a function of time, energy input (equivalent to temperature) and softness of the boundary. The approach to equilibrium is very slow, exhibiting a stretched exponential form. On raising the energy input a soft triangular billiard bifurcates from a stationary resting state to bouncing particle motion. However, as the enery input decreases, entropy production is dominated by large and rare fluctuations and the time to attain equilibrium diverges.

Guy Metcalfe
School of Mathematical Sciences
Monash University
guy.metcalfe@monash.edu

MS50

Nonlinear Energy Transfers in Fluid-Structure Interaction of a Cylinder with An Internal Attachment

We consider two-dimensional flow past a linearly-sprung cylinder allowed to undergo rectilinear motion normal to the mean flow, with an attached "nonlinear energy sink' (NES) consisting of a mass allowed to rotate about the cylinder axis, and whose rotational motion is linearly damped by a viscous damper. At $Re = 100$, the NES-equipped cylinder undergoes repetitive cycles of slowly decaying oscillations punctuated by chaotic bursts. During each slowly decaying cycle, the dynamics is regular and, for large enough values of a mass ratio ε, can lead to significant vortex elongation with partial stabilization of the wake. As ε approaches zero, no such vortex elongation

is observed and the wake is similar to that for an NES-less cylinder. Proper orthogonal decomposition (POD) of the flow field shows that the NES has a drastic effect on the underlying flow structures, imparting significant redistribution of energy among POD modes. We introduce a quantitative signed measure of the work done by the fluid on the cylinder and find that vortex elongation is associated with a sign change of that measure, indicating that a reversal of the direction of energy transfer, with the cylinder "leaking energy back' to the flow, is responsible for wake elongation. We relate these findings to the mechanism of transient resonance capture into a slow invariant manifold of the fluid–structure interaction dynamics.

Antoine Blanchard
University of Illinois - Urbana-Champaign
ablancha@illinois.edu

Lawrence Bergman
University of Illinois - Urbana - Champaign
lbergman@illinois.edu

Alexander Vakakis
University of Illinois
avakakis@illinois.edu

MS50

Extreme Control of Impulse Transmission by Cylindrical Phononic Crystals

Here we present a highly tunable periodic device that can offer two extremes of elastic wave propagation - nearly complete transmission and strong attenuation under impulse excitation. The device is a one-dimensional chain that consists of identical cylinders interacting as per nonlinear Hertzs contact law. Under no initial static compression, the system becomes an essentially non-linear system. We maintain two different contact angles, which periodically vary along the chain, and analyze the resulting dimer phononic crystal. We numerically and experimentally show that by choosing the appropriate set of contact angles, the impact excitation can either be localized and transmitted with minimum attenuation, or it can be highly dispersed leading to strong attenuation. Moreover, we use asymptotic analysis and show that there can be countable infinity of such contact angles. We close the discussion by highlighting the key characteristics of the mechanisms that facilitate strong attenuation of incident impulse. These include low-frequency to high-frequency (LF-HF) scattering, and turbulence-like cascading in this ordered system. We thus envision that these adaptive, cylinder based Phononic crystals, in conjunction with conventional impact mitigation mechanisms, could be used to design highly tunable and efficient impact manipulation devices.

Rajesh Chaunsali
University of Washington, Seattle
rajeshc@uw.edu

Eunho Kim
University of Washington
eunhokim80@gmail.com

Matthew Toles, Jinkyu Yang
University of Washington, Seattle
toles.matthew@gmail.com, jkyang@aa.washington.edu

MS50

Tailoring Dispersion Characteristics in Next-Generation Metastructures

This talk will review our efforts on metastructures that employ tailored dispersion characteristics for applications ranging from structure-borne wave focusing for enhanced energy harvesting to broadband vibration attenuation using locally resonant metamaterials. The two particular approaches for wave focusing are the use of elastic wave lens and mirror concepts. In the context of wave focusing by dispersion tailoring, we will discuss our computational and experimental results on a Gradient-Index Phononic Crystal Lens (GRIN-PCL) design for dramatically enhanced plane wave energy harvesting. The proposed GRIN-PCL is formed by an array of blind holes with different diameters on an aluminum plate where the orientation and size of the blind holes are tailored to obtain a hyperbolic secant distribution of refractive index. The design is guided by finite-element simulations of the lowest asymmetric Lamb wave mode dispersion to achieve the desired refractive index profile. We will also summarize our recent efforts on elastic wave focusing using structurally-embedded mirrors through finite-element simulations and experimental validations. Finally, low-frequency dispersion tailoring by means of locally resonant metamaterials will be discussed for broadband vibration attenuation through bandgap formation. Locally-resonant dispersion and bandgap characteristics (especially with changing mass ratio) will also be bridged to lens and mirror concepts to enable low-frequency wave focusing.

Alper Erturk
Georgia Institute of Technology
alper.erturk@me.gatech.edu

MS50

Nonlinear Mechanisms of the 2D Energy Redirection and Absorption in Mechanical Systems Subject to the External Loading

In the present talk I will discuss the recent results concerning the basic problem of energy transfer emerging in the 2D mechanical meta-materials with the internal, resonating inclusions. This study is mainly devoted to the analysis of special response regimes manifested by the 2D resonant energy transfer induced by the various types of external forcing.

Yuli Starosvetsky
Technion, Israel Institute of Technology
staryuli@tx.technion.ac.il

MS51

Globally Attracting Synchrony in a Network of Oscillators with Strong Inhibitory Pulse Coupling

The synchronization tendencies of networks of oscillators have been studied intensely in the context of fireflies, cardiac cells, Josephson junctions, laser arrays, chemical oscillators, hybrid dynamical systems, pulse-coupled sensor networks and neutrino flavor oscillations. We assume 1) all-to-all pulse-coupled oscillators, 2) the effect of a pulse is independent of the number of oscillators that simultaneously emit a pulse, 3)the phase resetting is a phase delay that is a monotonically increasing with slope everywhere less than one, (which implies the phase resetting has a strongly destabilizing discontinuity at the threshold for pulse emission which is strongly destabilizing and 4) the normalized delay (the phase resetting) lies everywhere to the left of the line $y = 2\phi - 1$, where ϕ is the phase. We then prove that synchrony is globally attracting for small conduction delays. Absorptions are allowed, therefore clusters can form. The requirement for the slope to be everywhere less than one precludes order switching, so the firing order, once established, must remain constant. Therefore the only possible solutions are globally synchrony and cluster solutions with a fixed firing order. The strategy is to prove the former stable and all other possible attractors to be unstable. We then extend these results to sparse networks.

Carmen Canavier
Louisiana State University Health Sciences Center
ccanav@lsuhsc.edu

Ruben Tikidji-Hamburyan
George Washington University
rath@gwu.edu

MS51

Entrainment Maps: A New Tool for Understanding Properties of Circadian Oscillators

Entrainment implies that an endogenous oscillator has matched its period to that of an external periodic forcing and has established a stable phase relationship with the forcing signal. The process of circadian entrainment has been studied extensively using tools from oscillator theory, in particular phase response curves (PRCs) that measure the change in the phase of an endogenous limit cycle oscillation (typically in constant darkness or DD) induced by a perturbation (typically a light pulse) as a function of the phase at which the perturbation is applied. Such PRCs can be constructed for light pulses of arbitrary strength and duration. However, for a PRC to accurately predict properties of entrainment to periodic light pulses, the perturbations must be weak or brief enough that the oscillator would relax back to the DD limit cycle attractor before the next pulse arrives. We show that PRCs do not accurately predict the phase of entrainment in a model of the Drosophila circadian clock subjected to photoperiods with substantial amounts of both light and dark, such as 12:12 light:dark (LD) cycles. In this talk, we introduce *entrainment maps*, which are one-dimensional maps that are not based on perturbing the DD oscillator and thus are able to accurately predict the phase of entrainment for any photoperiod.

Casey Diekman
Department of Mathematical Sciences
New Jersey Institute of Technology
casey.o.diekman@njit.edu

Amitabha Bose
New Jersey Institute of Technology
bose@njit.edu

MS51

A Map-Based Approach to Understanding Circadian Modulation of Sleep

A homeostatic need for sleep increases with time awake and decreases during sleep. In typical adult human parameter regimes, this homeostatic sleep drive produces one nighttime sleep episode per day. However, when the build up and recovery of sleepiness occurs sufficiently quickly, two sleep cycles per day, a nap as well as nighttime sleep, may occur. To investigate the transition between one and two sleep cycles per day, we analyzed bifurcations in a model for human sleep/wake dynamics as the time constants related to the build up and recovery of sleepiness are decreased. We found that the system exhibits an incremental increase in the number of sleep cycles per day. Using a one-dimensional map to represent the dynamics of the system, we relate this map to a normal form for a piecewise continuous system which undergoes a border collision bifurcation, and we provide numerical evidence for period-adding behavior. This analysis has implications for understanding the dynamics of the transition from napping to non-napping behavior in early childhood.

Cecilia Diniz Behn, Kelsey Kalmbach
Colorado School of Mines
Applied Math & Statistics
cdinizbe@mines.edu, kkalmbac@mymail.mines.edu

Victoria Booth
University of Michigan
vbooth@med.umich.edu

MS51

Farey sequences in Periodically Forced 2-Dimensional Integrate-and-Fire Models

In this talk we consider general two-dimensional integrate-and-fire models with a subthreshold attracting equilibrium and driven by a periodic forcing. Instead of considering the firing-map, we use the stroboscopic one, which is the usual tool for periodic smooth systems. It becomes a planar discontinuous map defined in different partitions given by the number of spikes performed at each iteration. Periodic orbits may bifurcate via tangent grazing or non-smooth grazing. We show that, in the latter case, the map may become a quasi contraction, and hence possesses periodic orbits whose symbolic dynamics are in the Farey tree. We also show that, when periodic orbits bifurcate close to a tangency, bistability may occur.

Albert Granados
COMPUTE Department
Technical University of Denmark
algr@dtu.ek

Gemma Huguet
Universitat Politecnica de Catalunya
Gemma.huguet@upc.edu

MS52

Gene Expression Dynamics with Stochastic Bursts: Exact Results for a Coarse-Grained Model

We describe a theoretical framework to analyze the dynamics of gene expression with stochastic bursts. Beginning with an individual-based model which fully accounts for the messenger RNA (mRNA) and protein populations, we propose an expansion of the master equation for the joint process. The resulting coarse-grained model is a reduced system describing only the protein population while fully accounting for the effects of discrete and fluctuating mRNA population. Closed form expressions for the stationary distribution of the protein population and mean first-passage times of the coarse-grained model are derived. Large-scale Monte Carlo simulations show that the analysis accurately describes the individual-based process accounting for mRNA population, in contrast to the failure of commonly proposed diffusion-type models. This is joint work with Yen Ting Lin.

Charles R. Doering
University of Michigan
Mathematics, Physics and Complex Systems
doering@umich.edu

MS52

Deterministic and Stochastic Effects in the Assembly of Multi-species Microbial Communities

Microbial communities play an essential role in determining both human health as well as the health of the planet. Over the last decade tremendous progress has been made in characterizing these complex microbial communities, but the lack of experimentally tractable model systems has made it difficult to discern the rules governing microbial community assembly and function. In this talk I will describe our recent experimental efforts to develop a bottom-up approach to community assembly. We have measured all pairwise competitive outcomes among 20 isolates from a single grain of soil, where we find a remarkably hierarchical structure with no rock-paper-scissors interactions. We find that simple assembly rules incorporating pairwise competitive outcomes are surprisingly successful in predicting the outcome of multi-species competition. Finally, we have begun to characterize community assembly within the gut of the worm C. elegans, where we find that stochastic colonization can drive strong heterogeneity between the microbial communities in different worms.

Jeff Gore
Massachusetts Institute of Technology
gore@mit.edu

MS52

Large Deviations for Gaussian Processes with Delay

Dynamical systems driven by nonlinear delay SDEs with small noise can exhibit important rare events on long timescales. When there is no delay, classical large deviations theory quantifies rare events such as escapes from metastable fixed points. Near such fixed points one can approximate nonlinear delay SDEs by linear delay SDEs. Here, we develop a fully explicit large deviations framework for (necessarily Gaussian) processes X_t driven by linear delay SDEs with small diffusion coefficients. Our approach enables fast numerical computation of the action functional controlling rare events for X_t and of the most likely paths transiting from $X_0 = p$ to $X_T = q$. Via linear noise local approximations, we can then compute most likely routes of escape from metastable states for nonlinear delay SDEs. We apply our methodology to the detailed dynamics of a genetic regulatory circuit, namely the co-repressive toggle switch, which may be described by a nonlinear chemical Langevin SDE with delay.

William Ott
University of Houston
ott@math.uh.edu

MS52

Rare Events Reconstruction of Most Likely Evolutionary Paths for Bacterial Populations

In this talk we present the large-deviation approach for computing the optimal trajectory for genetic evolution trajectories leading to the emergence of a-typical bacterial genotypes. In particular, we consider the stochastic dynamics of histograms of bacterial populations with n genotypes in a given fitness landscape. We consider radical shifts in the genetic composition of large cell populations and use the large-deviations approach to derive explicit cost function for paths connecting the initial and the final histograms. We then demonstrate that the minimizer of this cost function is the most likely evolutionary trajectory leading to the emergence of the final histogram of bacterial genotypes. We also develop a backward shooting numerical algorithm for effectively computing the most likely population trajectory linking any two successive genotype fixations (histograms) and to estimate the probabilities of these long term transitions. Numerical examples illustrating the approach will also be presented.

Ilya Timofeev
University of Houston
ilya@math.uh.edu

Robert Azencott
Department of Mathematics
University of Houston
razencot@math.uh.edu

Brett Geiger
University of Houston
geiger12@math.uh.edu

MS53

Canards in Stiction: On Solutions of a Friction Oscillator by Regularization

We consider the problem of the friction oscillator using the stiction model of friction. This friction law has a discontinuity between the dynamic and the static regime. The discontinuity set has a sticking region in which the forward solution is non-unique. In particular, there are special points along these segments where the solution is tangent to the boundary of the discontinuity set. In order to resolve this uncertainty, we introduce a regularization of the vector field and we obtain a multiple-time scale problem. Here the special points of the piecewise-smooth problem become folded saddles and a canard solution appears. We study the interaction of periodic orbits with the canard and we find that the the regularized problem has solutions that do not appear in the original problem.

Elena Bossolini
Technical University of Denmark
Department of Applied Mathematics and Computer Science
ebos@dtu.dk

Morten Brons
Tech University of Denmark
Department of Mathematics
mobr@dtu.dk

Kristian U. Kristiansen
Department of Mathmatics
Technical University of Denmark
krkri@dtu.dk

MS53

Overview of Models for Impact and Friction -

Oblique and Spatially Extended Systems

This talk will give an overview of recent work at Bristol and elsewhere on the dynamical systems aspects of the mechanics of frictional contact. The talk shall cover the strange dynamics of "rate and state" friction laws and why these are better experimentally motivated than pure Coulomb and related friction models. This is shown to reduce the non-smooth character of dynamics with friction to that of singularly perturbed systems. These results are illustrated using the classical sliding block model. It is then shown how things are more subtle if contact is not always maintained. An overview of some recent work on the so-called Painlevé paradox is given in which there is a coupling between tangential and normal degrees of freedom. It is shown how to unfold nondeterminism due to so-called dynamic jam, and reverse chatter using specialized desingularization methods. Finally the rate and state model is applied to a problem with continuous line contact. Phase plane analysis can then be used to capture both slip and stick transition waves and pulses as traveling fronts and waves, via phase plane analysis.

Alan R. Champneys, Thbaut Putelat
University of Bristol
a.r.champneys@bristol.ac.uk, a.veraart@imperial.ac.uk

MS53
On the Regularization of Impact Without Collision: The Painlevé Paradox and Compliance

Abstract Not Available At Time Of Publication.

S. John Hogan
University of Bristol
s.j.hogan@bristol.ac.uk

Kristian U. Kristiansen
Department of Mathmatics
Technical University of Denmark
krkri@dtu.dk

MS53
Dynamic Jamming Singularity of Mechanical Systems with Muliple Point Contacts

Abstract Not Available At Time Of Publication.

Peter L. Varkonyi
Budapest University of Technology and Economics
vpeter@mit.bme.hu

MS54
Optimal Balance via Adiabatic Invariance of Approximate Slow Manifolds

We analyze the method of optimal balance which was introduced by Viúdez and Dritschel to provide balanced initializations for two-dimensional and three-dimensional geophysical flows, here in the simpler context of a finite dimensional Hamiltonian two-scale system with strong gyroscopic forces. It is well known that when the potential is analytic, such systems have an approximate slow manifold that is defined up to terms that are exponentially small with respect to the scale separation parameter. The method of optimal balance relies on the observation that the approximate slow manifold remains an adiabatic invariant under slow deformations of the nonlinear interactions. The method is formulated as a boundary value problem for a homotopic deformation of the system from a linear regime where the slow-fast splitting is known exactly, and the full nonlinear regime. We show that, providing the ramp function which defines the homotopy is of Gevrey class 2 and satisfies vanishing conditions to all orders at the temporal end points, the solution of the optimal balance boundary value problem yields a point on the approximate slow manifold that is exponentially close to the approximation to the slow manifold via exponential asymptotics. We also give a numerical demonstration of the efficacy of optimal balance, showing the dependence of accuracy on the ramp time and the ramp function. This is joint work with G.A. Gottwald and H. Mohamad.

Marcel Oliver
Jacobs University Bremen
m.oliver@jacobs-university.de

MS54
A Quasi-Lagrangian Approach to Scalar Transport in Complex Flows

Dynamical systems-based Lagrangian methods can be used to identify key material boundaries and track transports in ocean and atmospheric flows with coherent structures. At the ocean surface, the velocity field used to compute fluid trajectories is often based on satellite altimetry, which typically resolves the geostrophically-balanced mesoscale flow. Contemporary models and observations are beginning to resolve the sub-mesoscale, which is typically unbalanced and which introduces a degree of complexity that can render standard methods cumbersome. In addition, oceanographers are often more interested in the fluxes of scalars such as heat, vorticity, salt and other biological and geochemical tracers than they are in the flux of fluid material. We suggest a new approach that reduces complexity through time filtering and that directly addresses nonmaterial, scalar fluxes. The approach is quasi-Lagrangian insofar as it contemplates trajectories of a velocity field related to a scalar flux, usually not the fluid velocity. Two examples are explored, the first coming from a canonical example of viscous adjustment along a flat plate and the second from a numerical simulation of a turbulent Antarctic Circumpolar Current in an idealized geometry. Each example concentrates on the transport of dynamically relevant scalars, and the second illustrates how substantial material exchange across a baroclinically unstable jet coexists with zero residual buoyancy flux.

Larry Pratt
Woods Hole Oceanographic Inst.
lpratt@whoi.edu

Roy Barkan
Dept. of Atmospheric and Oceanic Sciences, UCLA, Los Angeles
rbarkan@atmos.ucla.edu

Irina Rypina
Woods Hole Oceanographic Institution
irypina@whoi.edu

MS54
Multiscale Asymptotics for the Madden-Julian Oscillation and Tropical-extratropical Interactions

The Madden-Julian Oscillation (MJO) is a planetary-scale wave envelope of tropical clouds and precipitation, with modulations of hurricanes and tropical cyclones, and with contributions to active and break phases of monsoons. With a wavelength of 10,000-40,000 km and an oscillation period of 30-60 days, it stands at the intersection of weather and climate, and its prediction is a major challenge at the frontier of forecasting on weekly and monthly time scales. Multiscale asymptotic models will be presented for interactions between the MJO and extratropical waves. Such interactions include both (i) how the MJO can affect mid-latitude weather and climate, and, in turn, (ii) how extratropical waves can influence the initiation and termination of MJO events. The asymptotic models are derived from the nonlinear PDEs for the fluid dynamics of the atmosphere and the skeleton of the MJO, including the important effects of moisture and convection.

Shengqian Chen
University of Wisconsin, Madison
sqchen@math.wisc.edu

Andrew Majda
Courant Institute NYU
jonjon@cims.nyu.edu

Samuel Stechmann
University of Wisconsin - Madison
stechmann@wisc.edu

MS54

Nonuniqueness of Weak Solutions to the SQG Equation

We prove that weak solutions of the inviscid SQG equations are not unique, thereby answering an open problem posed by De Lellis and Szekelyhidi Jr. Moreover, we show that weak solutions of the dissipative SQG equation are not unique, even if the fractional dissipation is stronger than the square root of the Laplacian. This talk is based on a joint work with T. Buckmaster and S. Shkoller.

Vlad C. Vicol
Princeton University
Department of Mathematics
vvicol@math.princeton.edu

MS55

Self-assembled Structures in Copolymer-solvent Mixtures

Block copolymers are among the best candidate materials for synthetic nanoscale self-assembly. The interplay between microscopic phase segregation of polymer constituents and macrophase segregation between polymer and solvent produces a huge variety of morphologies. We employ a density functional model for mixtures of copolymer and solvent and its associated free boundary problem reduction. The simplest types of multilayered equilibria, those with translational symmetry (i.e. bilayers, multilayers) and radial symmetry (i.e. cylindrical and spherical micelles and vesicles), are considered in the context of this model. Their existence and stability will be discussed, as well as hybrid numerical/analytical approaches for their construction. In addition, possible scenarios for nonlinear evolution will be illustrated.

Karl Glasner
The University of Arizona
Department of Mathematics
kglasner@math.arizona.edu

Saulo Orizaga
University of Arizona
sorizaga@math.arizona.edu

MS55

Quenched Dynamics in the Symmetric Multicomponent Fch

Lipid bilayers are typically composed of many species of lipids with distinct intrinsic curvatures. We propose a model for multicomponent lipid bilayers of distinct aspect ratio and derive a curvature driven flow the exhibits a quenching phenomena in which the phase separation of lipids along the interface competes temporally with the relaxation of lipid density in the far field. The first process to reach equilibrium quenches the flow in the other process at leading order, leading to a degenerate flow at higher order. We present an analysis of the model.

Keith Promislow, Qiliang Wu
Michigan State University
kpromisl@math.msu.edu, qwu@math.msu.edu

MS55

Self-Organized Patterns in Networks of Electrochemical Reactions

Experiments with networks of discrete reactive bistable electrochemical elements, organized in regular and nonregular tree networks, are presented to confirm an alternative to the Turing mechanism for formation of self-organized stationary patterns. The results show that the pattern formation can be described by identification of domains that can be activated individually or in combinations. The method was also demonstrated to achieve localization of chemical reactions to network substructures and identification of critical sites whose activation results in complete activation of the system. The experiments were performed with a nickel electrodissolution system. Each unit in the network represented a corroding metal (nickel) wire that accommodated a complex reaction system with bistable behavior. Coupling was established in the form of the charge flow between the wires (due to difference in electrode potential) which affected the rate of metal dissolution of the coupled electrodes. The experiments reproduce all the salient dynamical behavior of a general network model with a single nonlinearity parameter describing the bistability. We also show that similar pattern formation can occur in star networks. The results are relevant for large random networks that possess locally the tree or star structure with relatively short-range effective interactions among the elements.

Michael Sebek
Saint Louis University
Department of Chemistry
msebek@slu.edu

Istvan Z. Kiss
Department of Chemistry
Saint Louis University
izkiss@slu.edu

MS55

Dynamics and Bifurcations in a Model for Organic Photovoltaic Cells

Organic photovoltaic (OPV) devices focus much attention due to their potential to provide economically viable sources of cheap, lightweight, renewable energy alternatives. One of the critical components of OPVs is the active layer labyrinthine-type donor/acceptor morphology, which allows relatively high efficiencies by increasing the surface area for charge generation. Nevertheless, theoretical studies of charge separation and transfer dynamics in OPVs thus far, had neglected the possible morphological evolution during operation. Consequently, a novel mean field model is being developed to incorporate the feedbacks between donor/acceptor morphologies and spatiotemporal charge properties, i.e., a nonlocal far from equilibrium theory. Specifically, the focus is on the bifurcations that govern the interfacial donor/acceptor properties and rich multi-phase structures, i.e., generation and sensitivity of the labyrinthine morphology. The approach is expected to provide a systematic understanding of OPV operation, and in particular to shed new light on degradation mechanisms related to morphological instabilities.

Alon Z. Shapira
Ben-Gurion University of the Negev
alonz678@gmail.com

Nir Gavish
Department of Mathematics
Technion ITT
ngavish@tx.technion.ac.il

Arik Yochelis
Jacob Blaustein Institutes for Desert Research,
Ben-Gurion University
yochelis@bgu.ac.il

MS56

Non-Intrusive Data Driven Reduced-Order Modeling Via Loewner Framework

We presents a data-driven nonintrusive model reduction approach for large-scale systems with linear state dependence. Traditionally, model reduction is performed in an intrusive projection-based framework, where the operators of the full model are required either explicitly in an assembled form or implicitly through a routine that returns the action of the operators on a vector. Our nonintrusive approach constructs reduced models directly from trajectories of the inputs and outputs of the full model, without requiring the full-model operators. These trajectories are generated by running a simulation of the full model; the method then infers frequency-response data from these simulated time-domain trajectories and uses the data-driven Loewner framework to derive a reduced model. Only a single time-domain simulation is required to derive a reduced model with the new data-driven nonintrusive approach. We demonstrate the propose methodology on benchmark examples and a finite element model of a cantilever beam.

Benjamin Peherstorfer
ACDL, Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
pehersto@mit.edu

Serkan Gugercin
Virginia Tech
Department of Mathematics
gugercin@vt.edu

Karen E. Willcox
Massachusetts Institute of Technology
kwillcox@MIT.EDU

MS56

A Geometric Approach to Dynamical Multiscale Model-Order Reduction

Any model order reduced dynamical system that evolves a modal decomposition to approximate the discretized solution of a stochastic PDE can be related to a vector field tangent to the manifold of reduced rank matrices. The Dynamically Orthogonal (DO) equations are the canonical reduced order model for which the corresponding vector field is the orthogonal projection of the original system dynamics onto the tangent spaces of this manifold. The embedded geometry of the fixed rank matrix manifold is analyzed. Differentiability results for projections onto embedded manifolds are utilized to obtain the differential of several truncated decompositions including the Singular Value Decomposition (SVD). The DO equations are shown to be the dynamical system that applies instantaneously the SVD truncation to optimally constrain the reduced solution. The geometric analysis is also used to discuss truncation errors and provide improved numerical time-integration schemes.

Pierre F. Lermusiaux, Florian Feppon
MIT
pierrel@mit.edu, feppon@mit.edu

MS56

Model Order Reduction for Stochastic Dynamical Systems with Continuous Symmetries

Stochastic dynamical systems with continuous symmetries arise commonly in nature and can display localized coherent structures, from hurricanes in the atmosphere to rogues waves at the ocean surface or vortices in the wake of marine mammals. Yet, because of their random locations, these structures are not well captured by current order reduction techniques and a large number of modes is typically necessary for an accurate solution. In this presentation, we introduce a new framework for efficient order reduction of such systems by combining (i) symmetry reduction tools from deterministic dynamical systems theory with (ii) dimensionality reduction techniques from the uncertainty quantification literature. We demonstrate the performance of our mixed symmetry-dimensionality reduction framework on stochastic solutions of the KdV and 2D Navier-Stokes equations.

Saviz Mowlavi
Massachusetts Institute of Technology
smowlavi@mit.edu

Themistoklis Sapsis
Massachusetts Institute of Techonology
sapsis@mit.edu

MS56

Data-driven Probability Density Function Equations for High-dimensional Stochastic Dynamical Systems

We present a new data-driven method to compute the probability density function (PDF) of a quantity of interest in high-dimensional stochastic dynamical systems. The key idea is to combine information from sample trajectories

with the exact evolution equation that governs the PDF of the quantity of interest. Such equation can be derived in rather general cases, e.g., by using the Lundgren-Monin-Novikov (LMN) approach (infinite-dimensional dynamical systems) or the Bogoliubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy of classical statistical mechanics (finite-dimensional dynamical systems). The closure approximation relies on estimating suitable conditional averages from sample trajectories. The effectiveness of proposed method will be demonstrated through various examples involving high-dimensional stochastic dynamical systems.

Daniele Venturi
Department of Applied Mathematics and Statistics
University of California Santa Cruz
venturi@ucsc.edu

MS57

Coupling Optimization Between Dynamical Units Using Ansatz Library and Global Modelling of Complex Network

When dynamical systems (units) are coupled to a complex network several challenging problems, such as finding the optimized coupling or obtaining a global model from a limited set of measurements, need to be solved. The Ansatz Library is a list of transformations applied to a nonlinear dynamical system - the unit of the network - into a standard form built from one of its variables and its successive derivatives. It can can be used to i) identify a class of nonlinear dynamical systems that are dynamically invariant, ii) identify the structure of the parameter space, iii) determine how to couple single dynamical systems, and iv) to obtain from one variable a global model expressed in terms of the variables spanning the original state space. Here we investigated the case of the Hindmarsh-Rose system, a simplified neuronal model, considered as the dynamical unit. When two Hindmarsh-Rose systems are coupled, the Ansatz Library can be used to show a drop in the dynamical complexity of the resulting network, especially when the two single units have (slightly) different time scales. The complexity drops further with every added dynamical unit. This transition between scales is an analogous to a transition from microscopic to macroscopic behavior. All these analytical results are then compared to digital as well as analog simulations.

Claudia Lainscsek
Salk Institute for Biological Studies
La Jolla, CA
claudia@salk.edu

Mark Spano
School of Biological and Health Systems Engineering
Arizona State University
mark.spano@mac.com

Christophe Letellier
Coria
Université de Rouen
letellier@coria.fr

Terrence Sejnowski
Salk Institute for Biological Studies
tjsejnowski@salk.edu

MS57

Assessing the Observability of Complex Networks: A Nonlinear Theory

Investigating the dynamics resulting from coupled oscillators whose frequencies are close is not new and was investigated in electronics for developing the wireless telegraphy. With the emergence of chaotic systems and, more recently, of complex networks, the problem of synchronizing (network of) coupled oscillators became widely studied due to the important applications it has not only in life and environmental sciences but also in power grids or social networks. As soon as a network is considered, the problem of the number of variables to measure required for its study is crucial because it is very often not possible to measure all of them. How to choose them is an important challenge which may depend on the task. We will introduce i) a nonlinear theory to obtain a full observability of the network dynamics as required for instance for getting a reliable and robust model and/or characterizing of its dynamics: a very challenging 13-dimensional rational dynamical network will be explicitly treated with an analytical validation of our results. ii) A procedure to choose a priori (before any attempt of coupling them) the best variable for full synchronizing (nearly) identical oscillators thus constituting a network will be outlined. We will show with few examples that the variables required for a full synchronizability are not necessarily the same as the ones for a full observability. How observability can be used in oncology will be briefly presented.

Christophe Letellier
Coria
Université de Rouen
letellier@coria.fr

MS57

Using Delay Coordinates for Quantifying Estimability of Model Parameters and State Variables from Observed Time Series

In data-driven system identification, values of parameters and not observed variables of a given model of a dynamical system are estimated from measured time series. We address the question of estimability and redundancy of parameters and variables, that is, whether unique results can be expected for the estimates or whether, for example, different combinations of parameter values would provide the same measured output. To answer these questions we analyze the null space of the linearized delay coordinates map [J. Schumann-Bischoff et al., Phys. Rev. E 94, 032221 (2016)]. This approach to estimability analysis can be generalized to multivariate time series and spatially extended systems or dynamical networks.

Ulrich Parlitz, Jan Schumann-Bischoff, Stefan Luther
Max Planck Institute for Dynamics and Self-Organization
Research Group Biomedical Physics
ulrich.parlitz@ds.mpg.de, jan.schumann-bischoff@ds.mpg.de, stefan.luther@ds.mpg.de

MS57

Inference of Dynamics from Network Observations

Networks of dynamical systems are common in applications, but rarely can all nodes be observed directly. It is known that strongly connected networks can be reconstructed, in theory, from any node. We examine practical limitations on the reconstruction, and propose quantitative measures on inference across networks.

Timothy Sauer
George Mason University, USA - Physica D, Elsevier
tsauer@gmu.edu

MS58

Wave Propagation in Models of mRNA Localization

Messenger RNA (mRNA) localization is essential during the development of frog egg cells into embryos. This accumulation of RNA at the cell periphery is not well understood, but is thought to depend on diffusion, bidirectional movement and anchoring mechanisms. We test these proposed mechanisms using linear and nonlinear PDE models and analysis, informed by numerical parameter estimation. Our results yield spreading Gaussian solutions for mRNA concentrations and confirm the hypothesis of bidirectional transport in localization.

Veronica M. Ciocanel
Brown University
veronica_ciocanel@brown.edu

Bjorn Sandstede
Division of Applied Mathematics
Brown University
bjorn_sandstede@brown.edu

Kimberly Mowry
Brown University
kimberly_mowry@brown.edu

MS58

Nondegeneracy of Antiperiodic Standing Waves for Fractional Nonlinear Schrödinger Equations

In the stability and blowup analyses for traveling and standing waves in nonlinear Hamiltonian dispersive equations, the nondegeneracy of the linearization about such waves is of paramount importance. That is, one must verify that the kernel of the second variation of the Hamiltonian is generated by the continuous symmetries of the PDE. The proof of this property can be far from trivial, especially when the dispersion admits a nonlocal description where shooting arguments, Sturm-Liouville theories, and other ODE methods may not be applicable. In this talk, we discuss the nondegeneracy of the linearization associated with antiperiodic constrained energy minimizers in a class of defocusing NLS equations having fractional dispersion. Key to our analysis is the development of ground state and oscillation theories for linear periodic Schrödinger operators with antiperiodic boundary conditions. The antiperiodic nature of the problem greatly complicates the analysis, as linear Schrödinger operators with periodic potentials need not have simple antiperiodic ground states even in the classical (local) case. As an application, we obtain the nonlinear (orbital) stability of antiperiodic standing waves with respect to antiperiodic perturbations.

Kyle Claassen, Mathew Johnson
University of Kansas
kclaassen@ku.edu, matjohn@ku.edu

MS58

Traveling Waves in Diatomic Fermi-Pasta-Ulam-Tsingou Lattices

We consider the problem of traveling waves in a diatomic Fermi-Pasta-Ulam-Tsingou lattice. We present recent results on the existence of periodic traveling wave solutions and the construction of nonlocal solitary wave solutions involving these periodic waves. In particular, we consider lattices with higher order terms in their nonlinear spring forces, which impose a technically complicated, but conceptually straightforward, reliance on composition operators.

Timothy E. Faver
Drexel University
tef36@drexel.edu

Doug Wright
Drexel University
Mathematics
jdoug@math.drexel.edu

MS58

The Maslov Index and the Spectra of Second Order Elliptic Operators

In this talk I will discuss a formula relating the spectral flow of the one-parameter families of second order elliptic operators to the Maslov index, the topological invariant counting the signed number of conjugate points of certain paths of Lagrangian planes. In addition, I will present formulas expressing the Morse index, the number of negative eigenvalues, in terms of the Maslov index for several classes of the second order operators: the $\vec{\theta}-$periodic Schrödinger operators on a period cell $Q \subset \mathbb{R}^n$, the elliptic operators with Robin-type boundary conditions, and the abstract self-adjoint extensions of the Schrödinger operators on star-shaped domains. This is joint work with Y. Latushkin.

Selim Sukhtaiev
Department of mathematics
University of Missouri
sswfd@mail.missouri.edu

MS59

Inertial Particles in Turbulence: Long Transients Due to the History Force

The motion of small inertial particles through a fluid is influenced by different hydrodynamic forces, described by the Maxey-Riley equations. One of these forces is the Basset force — an integral over the particle's history. We study the effects of the history force for nearly neutrally buoyant particles, exemplified by marine snow, advected by three-dimensional turbulent flow in the presence of gravity. We find that the presence of the history force in this system leads to individual trajectories that strongly deviate from what is observed without memory. However, the main effect of the Basset force is an extraordinarily slow convergence towards attractors. For our system with light aerosols we observe a power-law-type (proportional to $t^{-1/2}$) convergence to an asymptotic settling velocity of the center of mass of the particle ensemble, which is found numerically to be the settling velocity in a still fluid.

Ksenia Guseva
University of Oldenburg, Theoretical Physics/Complex Systems
Oldenburg, Germany
ksenia.guseva@uni-oldenburg.de

Anton Daitche
University of Munster
Germany
a.daitche@gmail.com

Ulrike Feudel
University of Oldenburg
ICBM, Theoretical Physics/Complex Systems
ulrike.feudel@uni-oldenburg.de

Tamas Tel
Eötvös Loránd University, Budapest, Hungary
Institute for Theoretical Physics
tel@general.elte.hu

MS59

Melancholia States in the Climate System

Multistability is a ubiquitous feature in systems of geophysical relevance and provides key challenges for our ability to predict a system's response to perturbations. Near critical transitions small causes can lead to large effects and - for all practical purposes - irreversible changes in the properties of the system. The Earth climate is multistable: present astronomical/astrophysical conditions support two stable regimes, the warm climate we live in, and a snowball climate. Following an idea developed by Eckhardt and co. for the investigation of multistable turbulent fluids, we study the global instability giving rise to the snowball/warm climate multistability by identifying the edge state, a saddle embedded in the boundary between the two basins of attraction. The edge state attracts initial conditions belonging to such a boundary and, while being defined using deterministic dynamics, is the gate facilitating noise-induced transitions between competing attractors. We use a climate model constructed by coupling a primitive equations model of the atmosphere with a simple diffusive ocean. We refer to the climatic edge states as Melancholia states and provide an extensive analysis of their features, relating thermodynamical properties to their dynamics and classifying them according to their symmetry. We discover cases where the Melancholia state has chaotic dynamics. We also identify a new stable climatic state characterized by non-trivial symmetry properties.

Valerio Lucarini
University of Hamburg
Meteorological Institute
v.lucarini@reading.ac.uk

Tamas Bodai
Meteorological Institute
University of Hamburg
tamas.bodai@uni-hamburg.de

MS59

State Space Structures of Decaying Shear Turbulence

In linearly stable shear flows on a finite domain, turbulence spontaneously decays on a characteristic transient lifetime. This lifetime sharply increases with Reynolds number. We relate the transient dynamics to structures in the state space of plane Couette flow. Based on the numerical analysis of decaying trajectories we discuss the emergence of the turbulence supporting chaotic saddle and the role of the edge-of-chaos during decay. Following the evolution of the chaotic saddle as a function of Reynolds number, we present a mechanism by which characteristic lifetimes increase.

Tobias M. Schneider
Emergent Complexity in Physical Systems Laboratory (ECPS)
Ecole Polytechnique Federale de Lausanne
tobias.schneider@epfl.ch

MS59

Probing the Edge of Chaos in Fluid Dynamics

We investigate the geometry of the edge of chaos and how the shape of the edge of chaos changes with increasing Reynolds number. The edge of chaos is the set of basin boundary points that are most immediately accessible from inside a basin boundary. We will also discuss ways in which a basin can suddenly be destroyed by small perturbations.

James A. Yorke
University of Maryland
Departments of Math and Physics and IPST
yorke@umd.edu

MS60

Extreme Growth of Enstrophy in Incompressible Flows

By solving suitable PDE-constrained optimization problems, we assess the sharpness of fundamental analytic estimates for the *instantaneous* rate of growth of certain Sobolev norms arising in the context of incompressible flows defined on two or three dimensional domains without boundaries. In the case of two-dimensional (2D) flows, the analytic estimates are found to be saturated by families of localized vortex fields parametrized by their H^{-1} and H^1 norms, providing evidence for the sharpness of the estimates. These instantaneously optimal vorticity fields are found to also saturate estimates for the *finite-time* growth of their H^1 norm under 2D incompressible Navier-Stokes dynamics. On the other hand, the corresponding estimate for three-dimensional (3D) flows is saturated by a family of localized vortex rings parametrized only by their H^0 norm, while other families of locally optimal fields are studied. Possible connections between these instantaneously optimal fields and the question about finite-time singularity formation are discussed.

Diego Ayala
Dept of Mathematics and Statistics
McMaster University
dayala@umich.edu

MS60

Computer Assisted Proof for the Navier-Stokes Equations: Existence of Periodic Orbits in a Taylor-Green Flow

The last decades saw the emergence and development of several techniques aiming at rigorously validating, a posteriori, the outputs of numerical simulations. Those methods (sometimes referred to as validated numerics or rigorous computations) were already successfully applied to a wide variety of problems, for instance to the study steady states, periodic orbits or traveling waves of specific PDEs. However, while the field of scientific computing has developed many very efficient algorithms to numerically study highly complex problems, validated numerics requires somewhat less efficient computations. Therefore we cannot hope to rigorously prove the most complicated solutions that can be numerically computed. Still, the refinement of the validated numerics techniques over the last few years, and the ever growing computational power available, make it so we can now start to tackle more and more complex problems, such as the Navier-Stokes equations. In this talk, I will present more precisely one of those rigorous validation methods, based on a computable kind of Newton-Kantorovich argument. I will try to emphasize its scope of application in fluid dynamics, and show how it can be used to prove the existence of periodic orbits for the Navier-Stokes equations with a given Taylor-Green forcing term.

Maxime Breden
ENS Paris-Saclay & Université Laval
maxime.breden@ens-cachan.fr

Jan-Philippe Lessard
Université Laval
jean-philippe.lessard@mat.ulaval.ca

Jan Bouwe Van Den Berg
VU University Amsterdam
Department of Mathematics
janbouwe@few.vu.nl

Lennaert van Veen
UOIT
lennaert.vanveen@uoit.ca

MS60

Energy Flux Enhancement via Triad Fourier Phase Dynamics in PDEs

In this work we present a study of Fourier-space phase dynamics in fluid dynamical PDEs with quadratic nonlinearity where triadic wavevector interactions are responsible for energy transport across scales. We examine in detail the dynamics of the triad Fourier phases, defined as triadic linear combinations of individual Fourier phases. The individual phases do not explicitly appear in the Fourier mode evolution equations in amplitude-phase representation. Instead, the 'dynamical' triad phase variables play an explicit role in governing the time evolution of the Fourier amplitude and phase variables. Our study of the influence of the dynamics of these triad phase variables on energy transfers include one-dimensional forced systems such as Burgers and Korteweg-de Vries/Burgers equation [Buzzicotti et al., EPJE, 39(3), 2016] and the two-dimensional Charney-Hasegawa-Mima equation [Bustamante et al., PRL , 113(8), 2014], relevant in atmospheric and plasma physics. In these cases we see strong correlations between the triad phase dynamics and the evolution of the amplitudes of Fourier modes in the triads, with intermittent (in time) alignment of triad phases leading to maximally efficient energy fluxes throughout the inertial range modes of the system. The careful analysis of these systems naturally leads us to a discussion as to how the distribution and dynamics of these Fourier triad phases may offer insight into energy fluxes in the case of isotropic Navier-Stokes turbulence.

Brendan Murray, Miguel Bustamante
University College Dublin, Ireland
brendan.murray@ucdconnect.ie,
miguel.bustamante@ucd.ie

Michele Buzzcotti, Luca Biferale
University of Rome Tor Vergata and INFN
michele.buzzicotti@roma2.infn.it, biferale@roma2.infn.it

MS60

The Onset of Turbulence in Large Eddy Simulation of Box Turbulence

Over the past three decades, the study of turbulence by means of computational dynamical systems theory has gathered ample momentum. One central goal is to find simple invariant solutions in Navier-Stokes flow in terms of which turbulence can be decomposed. Ultimately, this should allow us to explain the dynamics behind established scaling laws such as Kolmogorov's "-5/3" law for the energy spectrum and the log law for wall-bounded flow. So far, this goal has been out of reach because of the large number of degrees of freedom in turbulent flows, easily in the millions for flow with an inertial range, i.e. a sufficiently large separation of the spatial scales of energy input and dissipation. In large eddy simulation (LES) the motion on the smallest spatial scales, hypothesized to be unimportant to inertial range dynamics, is modelled by an effective dissipation. The resulting deterministic dynamical system describes inertial range dynamics, yet can be handled with modern computational methods. We study the bifurcation sequence that gives rise to LES turbulence in a Taylor-Green vortical flow at several truncation levels and discuss the peculiarities of LES, the successive breaking of symmetries and the development of the inertial range energy spectrum.

Lennaert van Veen
UOIT
lennaert.vanveen@uoit.ca

Tatsuya Yasuda
Imperial College
t.yasuda28@gmail.com

Genta Kawahara
Department of Mechanical Science
Osaka University
kawahara@me.es.osaka-u.ac.jp

Susumu Goto
Osaka University
goto@me.es.osaka-u.ac.jp

MS61

Data-Driven Models of Large-Scale, High-Dimensional Neural Recordings

Abstract Not Available At Time Of Publication.

Bingni W. Brunton
University of Washington
bbrunton@uw.edu

MS61

Data-Driven Discovery of Dynamical System Mod-

els for Biological Networks Using Sparse Selection and Information Criteria

Inferring the structure and dynamical interactions of complex systems is critical to understanding and controlling their behavior. As higher fidelity data becomes available, rapid generation and evaluation of mechanistically meaningful models from data is increasingly possible. We present a data-driven framework for sparse identification of nonlinear dynamical systems (SINDy). SINDy subselects a set of models from the combinatorial possibilities represented in the feature library. By integrating the Akaike Information Criteria (AIC) into the framework, we can rank the models in a principled way. The combined framework also allows us to mitigate measurement error, missing variables, incomplete feature libraries, and insufficient data. To enable discovery of a broader class of functions, we have also developed implicit-SINDy, which combines a compact feature library, implicit formulation, and sparsity promoting non-convex optimization. The method successfully identifies models for metabolic, regulatory and epidemiological networks. Rapid construction of such models could be leveraged for therapeutic gene modulation, metabolic engineering, or disease intervention.

Niall M. Mangan
Department of Applied Mathematics
University of Washington, Seattle
niallmm@uw.edu

Nathan Kutz
University of Washington
Dept of Applied Mathematics
kutz@uw.edu

Steven Brunton
University of Washington
sbrunton@uw.edu

Joshua L. Proctor
Institute for Disease Modeling
JoshLProctor@gmail.com

MS61

On Equation-Free Modeling for Large-Scale Infectious Disease Data

Equation-free techniques are poised to make substantial progress in the analysis of complex systems. In this talk, I will discuss a number of equation-free techniques, including the recently developed dynamic mode decomposition (DMD) and sparse identification of nonlinear dynamics (SINDy). Further, I will demonstrate how these methodologies can be applied to data sets collected from complex systems without a standard set of governing equations, specifically focusing on the spread of infectious disease. A data-driven understanding of how disease is spreading can help in the design of targeted intervention campaigns in resource-limited settings.

Joshua L. Proctor
Institute for Disease Modeling
JoshLProctor@gmail.com

MS61

Empirical Dynamics: An Equation-Free Approach for Understanding the Nonlinear Complex Systems Found in Nature

Abstract Not Available At Time Of Publication.

George Sugihara
Scripps Institution of Oceanography
University of California San Diego
gsugihara@gmail.com

MS62

Heteroclinic Switching Between Chimeras

The emergence of collective behavior is a fascinating feature of interacting oscillatory units in nature and technology. We give some recent results [Bick, C. (2017). Heteroclinic switching between chimeras. arXiv:1703.03274] how sequential switching of localized frequency synchrony—that is, localized groups of oscillators will frequency synchronize and desynchronize in a prescribed way—arises in networks of phase oscillators through generalized, nonsinusoidal coupling. Such dynamics may for example encode information in real world networks of oscillatory units.

Christian Bick
University of Exeter, UK
bick@maths.ox.ac.uk

MS62

Flexible Information Processing in Complex Networks

Flexible information processing fundamentally underlies the function of many biological and artificial networks. Yet, how such systems may specifically communicate and dynamically process information is not well understood. In this talk, I will first identify a generic mechanism to route information on top of collective dynamical reference states in complex networks akin to radio signals where information is encoded in the modulation of a carrier signal. Switching between collective dynamics induces flexible reorganization of information sharing and routing patterns, as quantified by delayed mutual information and transfer entropy measures between activities of networks units. I will then show how this mechanism provides a basis to achieve flexible computation in neuronal networks. In particular, coupled oscillatory Hopfield networks are shown to self-organize their collective reference dynamics so that only local information with high confidence is broadcasted across the entire network. This allows the network to perform coherent multi-modal pattern recognition even under conflicting input or context information. These results help understanding and designing information routing and processing across systems where collective dynamics co-occurs with a communication function.

Christoph Kirst
Center for Studies in Physics and Biology
Rockefeller University, US
Christoph.Kirst@Rockefeller.edu

MS62

Analysis of Cryptocurrencies Networks Using Google Trends Data

Various cryptocurrencies have emerged as possible competitors to fiat currencies, with the underlying blockchain technology spreading and gaining recognition. This talk is devoted to the application of nonlinear dynamics methods

to analyse and estimate the proliferation of cryptocurrencies. SIR type models are adapted to describe the take up and abandonment of the blockchain based technology by the general population. Publicly available Google Trends data is used for model validation and prediction testing, reflecting the interest generated by the cryptocurrencies discussed.

Aleksandra Ross
University of Sussex, UK
at370@sussex.ac.uk

MS62

Coherence-Resonance Chimeras in a Neural Network

We show that chimera patterns can be induced by noise in nonlocally coupled neural networks in the excitable regime. In contrast to classical chimeras, occurring in noise-free oscillatory networks, they have features of two phenomena: coherence resonance and chimera states. Therefore, we call them *coherence-resonance chimeras*[N. Semenova, A. Zakharova, V. Anishchenko, E. Schöll, Coherence-resonance chimeras in a network of excitable elements, Phys. Rev. Lett. 117, 014102 (2016)]. These patterns demonstrate the constructive role of noise and appear for intermediate values of noise intensity, which is a characteristic feature of coherence resonance. In the coherence-resonance chimera state a neural network of identical elements splits into two coexisting domains with different behavior: spatially coherent and spatially incoherent, a typical property of chimera states. Moreover, these noise-induced chimera states are characterized by alternating behavior: coherent and incoherent domains switch periodically their location. We show that this alternating switching can be explained by analyzing the coupling functions.

Anna Zakharova
Technische Universität Berlin
Berlin, Germany
anna.zakharova@tu-berlin.de

MS63

Synchronization and Survival of Connected Bacterial Populations

Migration plays a vital role in controlling population dynamics of species occupying distinct habitat patches. While local populations face extinction due to demographic or environmental stochasticity, migration from neighboring habitat patches can rescue these populations through colonization of uninhabited regions. However, a large migratory flux can synchronize the population dynamics in connected patches and enhance the risk of global extinction during periods of depression in population size. Here, we investigate this trade-off between local rescue and global extinction using laboratory populations of E. coli bacteria. Our model system consists of mutualistic co-cultures of ampicillin resistant and chloramphenicol resistant strains that exhibit period-3 oscillations in the relative population density in the presence of both antibiotics. We quantify the onset of synchronization of oscillations in a pair of cocultures connected by migration and show that period-3 oscillations are disturbed for moderate rates of migration. These results are consistent with simulations of a mechanistic model of antibiotic deactivation in our system. The simulations also predict that the probability of survival of connected populations in high concentrations of antibiotics is maximized at intermediate migration rates. We verify this prediction experimentally and show that survival is enhanced due to a combination of disturbance of period-3 oscillations and stochastic re-colonization events.

Shreyas Gokhale
Physics of Living Systems Group
Massachusetts Institute of Technology
gokhales@mit.edu

Arolyn Conwill
Massachusetts Institute of Technology
aconwill@mit.edu

Tanvi Ranjan
Harvard University
tanvi_ranjan@g.harvard.edu

Jeff Gore
Massachusetts Institute of Technology
gore@mit.edu

MS63

The Emergent Levy Behavior of Stochastic Burst Phenomenon in Single-cell Gene Expression

Single-cell gene expression is stochastic at the biochemical level; it can be represented by a Delbrück-Gillespie process describing the number of mRNAs and proteins in a volume V; it is known that in the macroscopic limit of $V \to \infty$ a deterministic chemical kinetics arises. We derive another, stochastic Lévy-process limit that agrees with the empirical equation of Friedman *et. al.* [Phys. Rev. Lett. 97:168302, 2006]. We establish two types of limits in which protein synthesis rate $\propto V$: One is deterministic corresponding to a cell-extract experiment in which DNA numbers $\propto V$ (Kurtz limit), another corresponds to a giant cell with DNA copy numbers independent of V but protein production per DNA $\propto V$ (Lévy limit). The latter conceptualizes the stochastic bursts of gene expression. A three-stage model with feedback regulation provides by far the most comprehensive analytic theory of the steady-state distribution of the protein concentration in single cells. Implication of the emergent Lévy behavior to biological phenotypic diversity is discussed.

Chen Jia
Department of Mathematical Sciences
University of Texas at Dallas
jcbeiboy@126.com

Michael Zhang
The University of Texas at Dallas
michael.zhang@utdallas.edu

Hong Qian
Department of Applied Mathematics
University of Washington
hqian@u.washington.edu

MS63

Mathematical Modelling of Organelle Transport in Living Cells

Two basic mechanisms for intracellular transport are motor-driven trafficking which usually occurs along microtubules (MTs) and diffusion which is inefficient to move over long distances. Recently, mathematical modelling approaches have been actively developed to understand such intracellular transport. We use live-cell imaging data in Ustilago hyphal cells and develop mathematical models to study mechanism underlying spatial organization of molecular motors and organelles. In particular, we found that stochastic motility of dynein motors along MTs contribute to half of its accumulation at hyphal tip to support early endosome recycling. The bidirectional transport of early endosome not only facilitates the directed motion of peroxisomes along MTs but also enhances their diffusive motion which is so-called active diffusion. Our modelling approach also suggests that directed transport and, to a lesser degree, active diffusion contribute to overcome the actin-based polar drift forces, to ensure even distribution of peroxisomes and support their mobility over short and long distances, respectively.

Congping Lin
huazhong university of science and technology
congpinglin@gmail.com

MS63

Analysis and Simulation of Multiscale Stochastic Intracellular Bio-chemical Reacting Networks

Intracellular reacting networks involving gene regulation often exhibits multiscale properties. That includes multiple reacting rates, multiple population magnitudes and multi-stability. Direct Stochastic Simulation Algorithm (SSA) would turn out to be inefficient dealing with such systems. Schemes such as Nested SSA and Tau-leaping method have proved to be effective for certain asymptotic regimes. Based on the framework of transition path theory (TPT), we extended the probability current between two adjacent reacting states to single reacting states as well as reacting trajectories, thereby give the definition of transition state (TS) as states with maximum velocity strength. I will present recent results on the convergence analysis and applications of the algorithms.

Di Liu
Michigan State University
richarddiliu@gmail.com

MS64

Emergence and Resilience of a New Alternative State in the Gulf of Maine

Sheltered shores in the Gulf of Maine previously contained two alternative states - mussel beds and stands of *Ascophyllum nodosum*. Over the last decade, mussels largely disappeared. Long-term data show that there are now two distinct rockweed states on sheltered shores, one dominated by *A. nodosum*, the other by *Fucus vesiculosus*. Experimental clearings to mimic ice scour were established during winter 1996-97 and half of the cleared plots were cleared again in winter 2010-11. Data sets before and after reclearing were used to examine development and resilience of both rockweed states. K-means clustering using the 'Before' dataset identified 4 groups; Controls, *Ascophyllum*, slow-growing and fast-growing *Fucus* stands. A discriminant function derived from these clusters assessed resilience of each state based on the 'After' dataset. All *Ascophyllum* stands were assigned as *Ascophyllum* stands after reclearing. Median time for establishment ($> 10\%$ cover) was 7 years and full recovery ($> 90\%$ cover) took 15-20 years. In contrast, recovery of *Fucus* stands was not as certain; only 33% of slow-growing stands but 80% of fast-growing *Fucus* stands were re-assigned after re-clearing. However, median recovery time of *Fucus* after re-clearing is fast (< 3 years). It appears elasticity is key to the resilience of *Fucus* stands but inhibition is key for *Ascophyllum* stands.

Steven Dudgeon
California State University Northridge
steve.dudgeon@csun.edu

Peter Petraitis
University of Pennsylvania
ppetrait@sas.upenn.edu

MS64

Emerging Models of Resilience: Introduction

How much disturbance can a system withstand while keeping its basic character? This basic question of resilience matters in many applications, particularly sustainability science and natural resource management. Despite its apparent simplicity, the question requires careful choices of how to represent disturbance and how to define "basic character" if one wishes to use dynamical systems to find a quantitative answer in metric terms. I will survey existing methods for measuring resilience, comparing their assumptions, strengths, and weaknesses. After summarizing key approaches and challenges in the field of resilience quantification, I will highlight recent mathematical progress in this area.

Katherine Meyer
University of Minnesota
meye2098@umn.edu

MS64

Information, Order and the Resilience of Living Natural and Human Systems

A problem of modeling the resilience of a complex adaptive system is that a shock or persistent change to the system may instigate interactions that have not been seen or imagined before. In ocean ecosystems the interactions among species are extensive and flexible. Surprise is frequent. DNA and memory are forms of information that channel the behavior of living agents towards order. Hollands learning classifier system, a rule based approach to modeling behavior, can address evolution through genetics or learning. We add the idea that agents acquisition and use of information is constrained by the cost of resolving the uncertainty associated with an opportunity. Agents then tend to interact with others with whom theyve become familiar; they form families, groups, and groups of groups, creating systematic, hierarchical order. This order is far from static; as groups interact they acquire a range of experiences. They are able to build upon this knowledge, adapting their behavior to new circumstances. This behavioral flexibility imparts resilience to individuals and to the overall system. It is what makes these systems so susceptible to surprising outcomes. With this approach, we reconsider the way humans and fish interact in the overfishing problem, arriving at the broad idea that sustainability and resilience require the information needed for self-organization of natural systems, thereby pointing to new ways to govern and design regulations restraining human activity.

James Wilson
University of Maine
jwilson@maine.edu

Carl P. Simon

University of Michigan
cpsimon@umich.edu

MS64

A Flow-Kick Framework for Exploring Resilience

Resilience is a slippery concept that has different meanings in different contexts. From a dynamical systems point of view, the different meanings of resilience are often about interactions between transient dynamics of a system and disturbance to the system. In this talk, we subject the flow of an autonomous system of ODEs to regular shocks ("kicks") of constant size and direction. The resulting *flow-kick* systems occupy a surprisingly under-explored area between deterministic and stochastic dynamics. Natural questions to ask include: Does the resulting flow-kick system equilibrate? If so, where? Is that a "desirable" region of state space? Does it represent resilience? What are the dynamics near the flow-kick equilibrium? And what can it tell us about a system subject to stochastic disturbances from a compact domain?

Alanna Hoyer-Leizel
Mount Holyoke College
ahoyerle@mtholyoke.edu

Sarah Iams
Harvard University
Cambridge, MA
siams@seas.harvard.edu

Ian Klasky, Victoria Lee, Stephen Ligtenberg
Bowdoin College
iklasky@bowdoin.edu, toreylee2@gmail.com,
stephen.ligtenberg@gmail.com

Katherine Meyer
University of Minnesota
meye2098@umn.edu

Mary Lou Zeeman
Bowdoin College
Department of Mathematics
mlzeeman@bowdoin.edu

MS65

Stochastic Population Models: The Dynamics of Invasion and Extinction

Large populations support many types of contagious diseases. Without intervention, it is assumed disease eradication would not happen. Yet, we see disease fadeout and reintroduction cycles in real world data for all but a few diseases. To accurately model such events, one must include stochasticity, or randomness. This talk will present some of the mathematical machinery used to analyze stochastic population models and understand the dynamics not captured in traditional deterministic modeling. Using these methods, we can predict when random events can drive a disease to extinction or conversely, reintroduce the disease as a large outbreak. Understanding extinction and invasion processes can provide insight on how to best use intervention controls to exponentially improve the probability attaining a desired state.

Lora Billings, Eric Forgoston
Montclair State University
Department of Mathematical Sciences
billingsl@mail.montclair.edu,
eric.forgoston@montclair.edu

Garrett Nieddu
Montclair State University
nieddug1@mail.montclair.edu

MS65

Modeling the Dynamics of Interacting Particles by Means of Stochastic Networks

Material science have been rapidly developing in recent years. A variety of particles interacting according to different kinds of pair potentials has been produced in experimental works. Looking into the future, one can imagine controlled self-assembly of particles into clusters of desired structures leading to the creation of new types of materials. Analytical studies of the self-assembly involve coping with difficulties associated with the huge numbers configurations, high dimensionality, complex geometry, and unacceptably large CPU times. A feasible approach to the study of self-assembly consists of mapping the collections of clusters onto stochastic networks (continuous-time Markov chains) and analyzing their dynamics. Vertices of the networks represent local minima of the potential energy of the clusters, while arcs connect only those pairs of vertices that correspond to local minima between which direct transitions are physically possible. Transition rates along the arcs are the transition rates between the corresponding pairs of local minima. Such networks are mathematically tractable and, at the same time, preserve important features of the underlying dynamics. Nevertheless, their huge size and complexity render their analysis challenging and invoke the development of new mathematical techniques. I will discuss some approaches to construction and analysis of such networks.

Maria K. Cameron
University of Maryland
cameron@math.umd.edu

MS65

A Kinetic Theory of Birth, Death, and Fission of Age-Structured Populations

Classical age-structured mass-action models such as the McKendrick-von Foerster equation have been extensively studied but they are structurally unable to describe stochastic fluctuations or population-size-dependent birth and death rates. We present a semi-Markov stochastic framework for populations that incorporate age-dependent birth, death, and fission rates. By defining multiparticle probability density functions, we derive a BBGKY-like hierarchy of kinetic equations for the stochastic evolution of an aging population undergoing birth, death, and fission. Moments of the hierarchy allows us to systematically connect deterministic age-dependent models with existing master equation approaches. Our results allow for an intuitive treatment of the stochastic dynamics of age- and population-dependent populations applicable to the study of demography, stem cell dynamics, and disease evolution.

Tom Chou
UCLA
Departments of Biomathematics and Mathematics
tomchou@ucla.edu

Chris Greenman

University of East Anglia
c.greenman@uea.ac.uk

MS65

Metastability and Intrinsic Extinction Risk in Finite, Interacting Populations

Demographic stochasticity corresponds to random fluctuations due to populations consisting of a finite number of individuals whose fates aren't perfectly correlated. Unlike their deterministic counterparts, the asymptotic behavior of models of closed populations experiencing demographic stochasticity is often trivial: eventually all populations go extinct in the ecological models without immigration, or all but one allele is lost in the population genetics models without mutation. These extinction events, however, may be preceded by long-term transients i.e. "metastable behavior.' For a very general class of stochastic models, I will discuss recent results on how (i) the log duration of this metastable behavior scales like the "landscape size' provided the mean-field model has an attractor supporting all species or genotypes and (ii) the metastable behavior, for large landscape size, is statistically governed by the attractors of the mean-field dynamics. The results rely on extensive use of large deviation theory, and will be illustrated with models of competing species and Wright-Fisher models with selection.

Sebastian Schreiber
University of California, Davis
sschreiber@ucdavis.edu

MS66

Frictional Instabilities and Squeak in Soft Contacts

Abstract Not Available At Time Of Publication.

Daniele Dini
Imperial College London
d.dini@imperial.ac.uk

MS66

Nonlinear Dynamic Response Predictions of Aeroengine Components with Frictional Interfaces

Abstract Not Available At Time Of Publication.

Norbert Hoffmann, Christophe Schwingschakl, Loic Salles
Imperial College, London
n.hoffmann@imperial.ac.uk,
c.schwingshackl@imperial.ac.uk, l.salles@imperial.ac.uk

MS66

The Rats Whiskers - Transduction of Stick-Slip Dynamics Via a Tapered Rod

Abstract Not Available At Time Of Publication.

Maysam Oldazimi, Cornelius Schwartz
University of Tubingen
maysam.oladazimi@student.uni-tuebingen.de,
cornelius.schwarz@uni-tuebingen.de

Thbaut Putelat
University of Bristol
a.veraart@imperial.ac.uk

MS67

Toward Understanding the Multi-Scale Coupling in Global Oceanic Flows

Large-scale currents and eddies pervade the ocean and play a prime role in the general circulation and climate. The coupling between scales ranging from $O(10^4)$ km down to $O(1)$ mm presents a major difficulty in understanding, modeling, and predicting oceanic circulation and mixing, where our constraints on the energy budget suffer from large uncertainties. Identifying the energy sources and sinks at various scales and geographic locations can reduce such uncertainty and yield insight into new parameterizations of nonlinear physical processes. To this end, we have developed a novel multi-scale analysis framework, which accounts for the spherical geometry of the problem, and allows one to simultaneously probe the dynamics in both space and time. We apply these tools to satellite altimetry data and to strongly eddying high-resolution simulations using General Circulation Models (POP and MITgcm). We investigate the contribution of various nonlinear mechanisms, such as baroclinic and barotropic instabilities, to the transfer of energy between scales at various locations, such as in western boundary currents, near the equator, and in the deep ocean.

Hussein Aluie, Mahmoud Sadek
University of Rochester
hussein@rochester.edu, msadek@ur.rochester.edu

Matthew Hecht
Los Alamos National Laboratory
mhecht@lanl.gov

Geoffrey Vallis
University of Exeter
g.vallis@exeter.ac.uk

MS67

Averaging, Large Deviations, and Stochastic Parameterization in a Slow-fast two-box Ocean Model

The author has recently emphasized the non-Gaussian quality of subgrid-scale terms in under-resolved ocean models [I. Grooms, A Gaussian-product stochastic Gent-McWilliams parameterization, Ocean Modelling 2016]. This talk explores the effects of this kind of non-Gaussian noise in a novel low-dimensional system of stochastic ODEs describing the mean temperature and salinity difference between the equatorial and polar oceans. The system has three time scales, corresponding to fast eddy dynamics, medium-fast relaxation of temperature towards the atmospheric temperature, and slow salinity evolution. The system exhibits a climatological distribution with Gaussian core and non-Gaussian rare event probability. We develop two levels of parameterizations based on slow-fast averaging theory: a deterministic parameterization and a multiplicative Gaussian parameterization. We explore the ability of these parameterized models to reproduce the climatological distribution and short-term forecasting of rare events. The results shed light on the qualitative differences to be expected from deterministic, Gaussian, and non-Gaussian stochastic parameterizations in more complete ocean models.

Ian Grooms
Department of Applied Mathematics

University of Colorado, Boulder
ian.grooms@colorado.edu

William Barham
University of Colorado, Boulder
Applied Mathematics
william.barham@colorado.edu

MS67

Inertial Particles in a Vortical flow: Dynamics and Data

Two questions will be addressed: (1) What is the dynamical evolution of a particle with small inertia when placed near a vortex center, and (2) if the positions of such a particle are observed, how does the error propagate in tracking the vortex center by assimilating these data as if they were based on observations of a fluid particle.

Chris Jones, Colin Guider
University of North Carolina-Chapel Hill
ckrtj@email.unc.edu, cguider1@live.unc.edu

MS67

Seasonal to Annual Ocean Predictions and the Importance of Estimating Uncertainties

Seasonal forecasts of the climate system present a major challenge. Skilful forecasts on timescales of up to a year can have large societal implications. Accurately modelling the slowly evolving ocean is essential for such predictions, as it carries anomalies much longer than the more rapidly fluctuating atmosphere. Aside from accurately modelling the ocean state, it is crucial to understand and account for uncertainties in predictions to enable informed decisions. Ensemble simulations are commonly used to produce probabilistic forecasts that provide estimates of forecast uncertainty. In addition to irreducible uncertainties associated with the chaotic climate system, there are three major sources of uncertainty: Initial condition, model, and observational uncertainty. The 10-month forecast skill of the seasonal forecasting system of the European Centre for Medium- Range Weather Forecast will be discussed, focusing on the ocean component. Novel stochastic perturbation techniques are used to estimate model uncertainties in highly parametrized oceanic processes. Additionally, observational uncertainties - associated with the choice of the reference reanalysis used for forecast skill evaluation - will be analysed. Both kinds of uncertainty will be investigated in probabilistic ensemble predictions.

Stephan Juricke
Jacobs University Bremen
s.juricke@jacobs-university.de

MS68

Three-Timescale Dynamics: Canards and Spike Adding

In this talk, we will study a minimal three-timescale model of van der Pol type. This model displays periodic solutions that mimic bursting dynamics without having two clear fast variables. Using geometric singular perturbation theory as well as numerical bifurcation methods, we investigate how such bursting orbits grow more spikes as a system parameter is varied. In particular, we focus on two separate canard mechanisms providing key components of these spike-adding transitions.

Mathieu Desroches
INRIA Paris-Rocquencourt
mathieu.desroches@inria.fr

Vivien Kirk
University of Auckland
v.kirk@auckland.ac.nz

MS68

Canards in a Minimal Piecewise-linear Square-wave Burster

In this talk we show how to construct a piecewise-linear (PWL) approximation of the Hindmarsh-Rose (HR) neuron model that is minimal, in the sense that the vector field has the least number of linearity zones, in order to reproduce all the dynamics present in the original HR model with classical parameter values. This includes square-wave bursting and also special trajectories called canards, which possess long repelling segments and organise the transitions between stable bursting patterns with n and $n+1$ spikes, also referred to as spike-adding canard explosions. We propose a first approximation of the smooth HR model, using a continuous PWL system, and show that its fast subsystem cannot possess a homoclinic bifurcation, which is necessary to obtain proper square-wave bursting. We then relax the assumption of continuity of the vector field across all zones, and we show that we can obtain a homoclinic bifurcation in the fast subsystem. We use the recently developed canard theory for PWL systems in order to reproduce the spike-adding canard explosion feature of the HR model.

Soledad Fernández-García
University of Sevilla, Sevilla, Spain
soledad@us.es

MS68

Synchronisation of Weakly Coupled Canard Oscillators

Synchronization has been studied extensively in the context of weakly coupled oscillators using the so-called phase resetting curve (PRC) which measures how a change of the phase of an oscillator is affected a small perturbation. This approach was linked to the work of Malkin, and it has been extended to relaxation oscillators. Namely, synchronization conditions were established under the weak coupling assumption, leading to a criterion for the existence of synchronous solutions of weakly coupled relaxation oscillators. Previous analysis relies on the fact that the slow nullcline does not intersect the fast nullcline near one of its fold points, where canard solutions can arise. In the present talk we show how to use numerical continuation techniques in order to solve the adjoint equations and we show that synchronization properties of canard cycles are different than those of classical relaxation cycles. In particular, maximal canards separate two distinct synchronization regimes: the Hopf regime and the relaxation regime. Phase plane analysis of slow-fast oscillators undergoing a canard explosion provides an explanation for this change of synchronization properties across the maximal canard.

Elif Koksal Ersoz
INRIA de Paris

elif.koksal@inria.fr

MS68

Faux Canards and Folded Saddles

We study the two parameter family of faux canards associated with the folded saddle singularity within the folded singularity normal form. Recently, rotational behaviour of folded saddle faux canards has been reported and merits a closer look at faux canards which have been somewhat neglected in the literature. We address this gap in canard knowledge providing a comprehensive analysis of folded saddle faux canards, both numerically and analytically. We show that for certain values of μ – the eigenvalue ratio of the associated folded singularity within the reduced flow – faux canards may possess rotations about the primary faux canard, and that the stable and unstable fast manifolds (i.e. the nonlinear stable and unstable fast fibre bundles) of the primary faux canard form the boundaries of sets of solutions with similar rotational behaviour. This is in contrast to the folded node case where the stable and unstable slow manifolds of the primary weak canard organise the family of weak canards. We develop a numerical scheme by which we obtain these fast manifolds and locate and characterise the family of secondary faux canards and their bifurcations. We confirm the bifurcations of secondary faux canards via an extended Melnikov analysis where we find an alternating pattern of bifurcations – transcritical and pitchfork – similar to the alternating pattern of bifurcations of secondary weak canards in the case of the folded node.

John Mitry
University of Sydney
john.mitry@gmail.com

MS69

Spatial and Social Interactions Drive Transmission Dynamics in Ant Colonies

Social behavior in human and animal populations gives mobility to infectious disease. In some cases, being in close proximity of an infected individual can be enough for transmission to occur. On the other hand, diseases that require more intimate contact depend on social behaviors rather than spatial factors. Here we map the social network of an ant colony and ask whether ants structure their society in a way which mitigates the risk of epidemic disease? Most carpenter ants do not leave the nest. A few foragers ingest the food they find, and the food is transmitted through the colony on their return, resulting in a complex network of feeding interactions. In a lab experiment, we filmed several hours of nest activity. Based on the interactions recorded, we construct temporal networks where nodes are ants and edges are feeding interactions. Remarkably, the individuals in the ant colony are marked by a propensity to seek out new connections rather than repeat previous ones, contrary to what is seen in most other social animals and humans. To address whether this behavior encourages disease spread we use a model in which we can adjust the heterogeneity of social tie strength. We then couple this with a disease model where transmission depends non-linearly on the intensity of the interaction. Our analysis suggests that a rigid social structure determines the dynamics of communicable disease in carpenter ant colonies more so than spatial restrictions.

Shweta Bansal
Dept. of Biology
Georgetown University
shweta.bansal@georgetown.edu

Ewan Colman
Georgetown University
shweta.bansal@georgetown.edu

MS69

After the Honeymoon, the Divorce: Unexpected Outcomes of Disease Control Measures

We lack effective vaccines for many infections, so disease control measures often instead attempt to directly reduce transmission. As an example, the main control measure for the the mosquito-borne dengue virus has been mosquito control, e.g. by spraying insecticide aimed at adult insects. In this talk we discuss counter-intuitive behavior that can result when such control measures are employed for a transient period against an endemic infection. Building on an observation in a recent study of Okamoto et al., we demonstrate the epidemiologically-troubling result that there can be time windows over which the total number of disease cases can exceed the number that would have occurred if no intervention had been employed: accumulation of susceptibles during the control can lead to a large outbreak following the end of the control. This outbreak can be so severe that all the benefit accrued during control can be overcome. We show that this phenomenon can occur in a broad class of infection models and discuss public health implications, including for clinical trials of proposed control measures.

Alun Lloyd
North Carolina State University
alun_lloyd@ncsu.edu

Brandon Hollingsworth
NC State University
bhollin@ncsu.edu

Fred Gould
North Carolina State University
fred_gould@ncsu.edu

Kenichi Okamoto
Yale University
kenichi.okamoto@yale.edu

MS69

Effectiveness of Unaids Targets and Hiv Vaccination Across 127 Countries

The HIV pandemic continues to evolve, with AIDS-related deaths on the rise in regions of Asia and an increasing proportion of infections in sub-Saharan Africa are among adolescents. Simultaneously, advances in antiretroviral therapy, diagnostic approaches and vaccine development are providing novel tools for treatment-as-prevention and prophylaxis. We developed a mathematical model to evaluate the added benefit of an HIV vaccine in the context of goals to increase rates of diagnosis, treatment, and viral suppression in 127 countries. Under status quo interventions, we predict a median of 49 million [1st and 3rd quartiles 44M, 58M] incident cases globally from 2015 to 2035. Achieving the UNAIDS 95–95–95 target was estimated to avert 25 million [20M, 33M] of these new infections, and an additional 6.3 million [4.8M, 8.7M] reduction was projected with the 2020 introduction of a 50%-efficacy vaccine grad-

ually scaled up to 70% coverage. This added benefit of prevention through vaccination motivates imminent and ongoing clinical trials of viable candidates to realize the goal of HIV control.

Jan Medlock
Oregon State University
Department of Biomedical Sciences
jan.medlock@oregonstate.edu

Abhishek Pandey
Department of Biostatistics, Yale University
abhiganit@gmail.com

Alyssa S. Parpia, Amber Tang, Laura A. Skrip, Alison P. Galvani
Yale University
alyssa.parpia@yale.edu, amber.tang@yale.edu, laura.skrip@yale.edu, alison.galvani@yale.edu

MS69

Rationally Time-shifting Risk in Response to Zika

The morbidity of Zika infection varies depending on the age of infection. Infection is usually mild, but is associated with serious birth defects during pregnancy. Thus, costs from infection for women of child-bearing age have the potential to be much larger than for younger and older woman. This raises a conundrum similar to Rubella's – early infection greater susceptibility may reduce median infection ages and costs. In this talk, I'll pose a time-dependent differential population game model of Zika transmission and numerically solve for the rational social-distancing strategy. The solutions will be compared to optimal public policies, and costs of cooperation will be discussed.

Timothy Reluga
Pennsylvanian State University
treluga@math.psu.edu

MS70

Stability of Tree-Grass Interactions under Woody Encroachment

Woody encroachment of grasslands is occurring and accelerating across the globe. Dynamical systems approaches are often used in assessing the stability of the woody and grass end member states. Here, we investigate the roles of precipitation frequency and intensity and fire frequency on controlling the rate of the conversion of grasslands to woody dominated systems. We investigate these interactions using data from the Konza Prairie Long Term Ecological Research Site in North-Central Kansas. A low-dimensional model with stochastic precipitation and fire disturbance is introduced to examine the complex interactions between precipitation and fire as mechanisms that may suppress or facilitate increases in woody cover. We use Lyapunov exponents to ascertain the relative control exerted on woody encroachment through these mechanisms. Our results indicate that precipitation frequency is a more important control on woody encroachment than the intensity of individual precipitation events. Fire, however, exerts a much more dominant impact on the limitation of encroachment over the range of precipitation variability considered here.

Nathaniel A. Brunsell
Dept of Geography & Atmospheric Science, U Kansas
brunsell@ku.edu

Erik Van Vleck
Department of Mathematics
University of Kansas
erikvv@ku.edu

Jesse Nippert
Kansas State University
nippert@ksu.edu

Maged Nosshi
University of Kansas
mnosshi@ku.edu

Zak Ratajczak
University of Virginia
zaratajczak@gmail.com

MS70

Unifying Ecological Models for Understanding and Prediction

Ecological theory surrounding populations and communities of biological species is embedded in a series of basic but distinct mathematical models, including differential equation models for logistic growth, competition, and predation. The basic models parallel the historical development of ecology over the twentieth century. However, distinctions among the models are only apparent – all convert to a common quadratic form differing only in the signs of their parameters. Considering this common form reveals ecological dynamics that have long been missing or ignored in the existing subset of equations, yet are necessary to understand certain dynamics crucial in the modern world, including the global population of our own species. Here we explain the common form, expose the formerly missing parts, bring out some mathematical points remaining undeveloped, and show how the models explain and predict ecological observations at the Cedar Creek field station and in the world.

Clarence Lehman
University of Minnesota
lehman@umn.edu

MS70

Toward a Mathematical Theory of Resilience

Many ecological systems exhibit multiple equilibrium states, and questions arise regarding how resistant or resilient they are to perturbations or to changing environmental conditions. The classical concept of hysteresis is often used to explore whether a system will return to its previous state if the environment is returned to its previous condition. In this lecture we discuss the notion of the "intensity" of an attractor and examine how it can be used to quantify resilience. An example of plant community responses to nutrient changes will be explored.

Richard McGehee, Katherine Meyer
University of Minnesota
mcgehee@umn.edu, meye2098@umn.edu

MS70

Parameter Estimation for Land-Surface Models

In this talk we consider a projected shadowing based data assimilation technique for simultaneous state space and parameter estimation. Application of these techniques is considered for land-surface models ranging from a low dimensional water balance model with stochastic forcing for fire and precipitation to a complex model, Noah-MP, that allows for thousands of parameter combinations.

Erik Van Vleck
Department of Mathematics
University of Kansas
erikvv@ku.edu

Nathaniel A. Brunsell
Dept of Geography & Atmospheric Science, U Kansas
brunsell@ku.edu

MS71

Interconnection and Multiple-Investment Strategies in Energy Markets

This talk proposes a general economics model for the supply and demand of a commodity in a domestic market when investments are required for supporting it. Piecewise smooth and hybrid dynamical systems have been increasingly used in Engineering and Applied Sciences. More recently, these systems appeared also in Economics and Social Science, mainly in Sustainability Development, Bioeconomics, and new knowledge areas. Usually, the problem of one surface dividing the state space into two different regions is considered. In this paper, several switching surfaces are taken into account, since our application lies on this multi-surface situation. When several markets are connected, complex networks (in the dynamics and structure) naturally appear. Finally, stochasticity is introduced into the system to model the risk aversion of investment agents. This is done through Markov Chains. This combination of deterministic paths and stochasticity leads to the so-called Piecewise-Deterministic Markov Processes. Depending on the risk behavior, simulations show several decision patterns.

Gerard Olivar
Department of Electrical and Electronics Engineering
Universidad Nacional de Colombia, sede Manizales
golivart@unal.edu.co

Johnny Valencia Calvo
Tecnologico de Antioquia
johnny.valencia@tdea.edu.co

Oscar Emilio Molina Diaz
Universidad del Quindio
omolina@uniquindio.edu.co

MS71

Desynchronising Collections of Oscillators by Using Two-Fold Singularities

In this talk I will present possibly the first practical application of a two-fold — a singular point in a nonsmooth system of differential equations at which the long-term dynamics is, in a sense, infinitely sensitive to random perturbations. By applying a well-chosen control signal one can create a two-fold in a generic oscillatory system that has the effect of randomising the phase of the motion in a highly efficient manner. Such control signals could be used to break the synchrony of collections of oscillators with several advantages over more traditional methods.

David J. Simpson
Institute of Fundamental Sciences
Massey University
d.j.w.simpson@massey.ac.nz

Mike R. Jeffrey
University of Bristol
mike.jeffrey@bristol.ac.uk

MS71

Pausing: Revealing Time Indeterminacy in Piecewise Smooth Systems

Continuity in a dynamical system is known to not be a sufficient property to guarantee the uniqueness of its solutions. Here we consider piecewise smooth systems where ambiguity arises when the temporal determinacy of a solution is lost - pausing. In phase-space this corresponds to the same spatial trajectory being traversed in different times, as the solution pauses arbitrarily long at particular points. This potentially mimics behaviour seen in earthquakes and static friction models, where periods of dynamic activity are separated by seemingly static phases of unpredictable length. We study piecewise smooth systems containing temporal (and sometimes spatial) ambiguities that can be partly resolved through application of parameter rescalings and asymptotic balancing; except at particular parameter values where the uncertainty persists. These are our pausing points. We present examples of the phenomena occurring at a fold-fold singularity in a system drawn from a gene regulation model, and in the impacting system of the classical Painlevé paradox.

Simon C. Webber
University of Bristol
Department of Engineering Mathematics
scwebber.2011@my.bristol.ac.uk

Mike R. Jeffrey
University of Bristol
mike.jeffrey@bristol.ac.uk

Paul Glendinning
the University of Manchester
paul.glendinning@manchester.ac.uk

MS71

Coherent Behaviour in Non-Smooth Neural Networks

Certain neural systems show computation through patterned activity: persistent localised activity, in the form of bumps, has been linked to working memory, whilst the propagation of activity in the form of waves has been associated with binocular rivalry tasks. Individual neurons typically exhibit an all-or-nothing response, dependent on the summation of signals they receive from the rest of the network. This fact, coupled with the desire to understand coherent patterns of activity across the network has resulted in the widespread use of non-smooth neural models that greatly simplify the complex dynamics of individual cells. Whilst these descriptions often provide tractable models of neural tissue, their non-smooth nature presents its own mathematical challenges. We will show how localised bumps of activity and travelling waves are generated in a synaptically coupled neural network and how they lose stability through bifurcations of both smooth and non-smooth type. This will be done through the construction of interface equations that take advantage of the non-smooth nature of the model. We will examine how this can be used to explain the experimentally observed activity in grid cells, which are a significant component of the brain's representation of spatial location within an environment. Finally, we will present an approach to the asses impact of temporal and spatial noise in neural networks using numerical coarse-graining procedures.

Kyle Wedgwood
University of Exeter
k.c.a.wedgwood@exeter.ac.uk

Daniele Avitabile
School of Mathematical Sciences
University of Nottingham
Daniele.Avitabile@nottingham.ac.uk

Joshua Davis, Stephen Coombes
University of Nottingham
joshua.davis@nottingham.ac.uk,
stephen.coombes@nottingham.ac.uk

MS72

Delay-Induced Dynamics in An El Niño Southern Oscillation Model: A Bifurcation Analysis

We consider a conceptual model for the El Niño Southern Oscillation system in the form of a delay differential equation that includes feedback loops between the ocean and atmosphere. A bifurcation analysis demonstrates that qualitatively realistic behaviour results from the interplay between delayed feedback and seasonal forcing. Moreover, the model features the phenomenon of folding invariant tori, which may be interpreted as a form of climate tipping.

Andrew Keane
The University of Auckland
a.keane@auckland.ac.nz

Bernd Krauskopf
University of Auckland
Department of Mathematics
b.krauskopf@auckland.ac.nz

Claire M. Postlethwaite
University of Auckland
c.postlethwaite@auckland.ac.nz

MS72

Poincaré-Bendixson-Type Theorems for Equations with State-Dependent Delay

We will discuss classes of scalar-valued differential equations with state-dependent delay and monotone feedback for which Poincaré-Bendixson-type theorems do and do not hold. This work builds, most particularly, on work of Mallet-Paret and Sell from the 1990s.

Benjamin Kennedy
Gettysburg College
Department of Mathematics
bkennedy@gettysburg.edu

MS72

Nicholson Blowflies Dynamics in a Heterogenous Environment for Juveniles

In [WSC Gurney, SP Blythe, and RM Nisbet. Nicholson's blowflies revisited. *Nature*, 287:17–21, 1980],

$$x'(t) = -\gamma x(t) + px(t-\tau)e^{-\alpha x(t-\tau)}, \quad p, \alpha, \gamma, \tau > 0$$

is proposed to model oscillations in *lucilia cuprina* populations. In this model, $\frac{1}{\alpha}$ is the size of the population at which it achieves maximal reproduction success, γ is the adult death-rate, and parameter p is the maximal egg-production rate. We report on the effect of considering two maturation sites with different maturation times. That is, we consider

$$x' = -\gamma x + p\left(qe^{-\delta_1\tau_1}f(x(t-\tau_1)) + (1-q)e^{-\delta_2\tau_2}f(x(t-\tau_2))\right).$$

Our main interest is to investigate how the stability and oscillatory properties of the blowflies equation are affected by the heterogeneity of the maturation sites.

Gabor Kiss, Gabor Kiss
University of Szeged
robag.ssik@gmail.com, robag.ssik@gmail.com

MS72

Stability in a Neural Network with Distributed-Delay Coupling

In this talk I will present a Hopfield-type neural network model, where one sub-system receives a delayed input from another subsystem [B. Rahman, K.B. Blyuss & Y. N. Kyrychko *Dynamics of neural systems with discrete and distributed time delays*, SIAM Journal on Applied Dynamical Systems, 14 **(4)**, pp. 2069–2095 (2015).]. The model includes a combination of both discrete and distributed delays, where distributed time delays represent the neural feedback between the two sub-systems, and discrete delays describe the neural interactions within each of the two subsystems. Stability properties are investigated for different commonly used distribution kernels, and the results are compared to the corresponding results on stability analysis for networks with no distributed delays. I will show how boundaries of the stability region of the trivial equilibrium can be obtained analytically for the cases of delta, uniform and gamma distributions. Direct numerical simulations that confirm analytical findings will also be presented.

Yuliya Kyrychko
University of Sussex, UK
y.kyrychko@sussex.ac.uk

MS73

Meanfield Coupling of Expanding Circle Maps

We study the synchronization phenomena that arises when increasing the interaction strength in globally coupled circle maps. Specifically, we focus on the case when the individual site dynamics are doubling maps which interact by a mean field diffusive coupling of strength ε. In this setting and for finitely many sites, two distinct bifurcation values of the coupling strength have been identified in the literature, corresponding to the emergence of contracting directions (Koiller & Young, Nonlinearity, 2010) and, specifically for $N = 3$ sites, to the loss of ergodicity (Fernandez, Journal of Stat. Phys. 2014). In our recent paper (Bálint & Sélley, Journal of Stat. Phys. 2016), on the one hand, we reconsider these results and provide an interpretation of the observed dynamical phenomena in terms of the synchronization of the sites. On the other hand, we initiate a new point of view which focuses on the evolution of distributions and allows to incorporate the investigation

of a continuum of sites. In particular, we observe phenomena that is analogous to the limit states of the contracting regime of $N = 3$ sites. In this talk, we would like to present these results and describe possibilities for generalization to other values of N, other types of site dynamics and other forms of the coupling.

Peter Balint
Institute of Mathematics
Budapest University of Technology and Economics
pet@math.bme.hu

Fanni Mincsovicsne Selley
Budapest University of Technology and Economics
Department of Stochastics
selley@math.bme.hu

MS73

Generation of Stable Traveling Waves in Unidirectional Chains of Idealized Neural Oscillators

Phase oscillator ensembles exhibiting a preferred direction of coupling are a much studied topic of mathematical neuroscience, where they provide a framework for understanding the generation and propagation of electrical impulses across brain tissues. We report here on some recent successes in establishing stability of traveling wave solutions (TW) in feedforward chains of idealized neural oscillators featuring a pulse emission / Type-I phase response (PRC) interaction. In prior work, the smooth version of this model was studied through a combined numerical / analytical methodology: an iterative fixed point scheme was used to verify existence of TW; these findings then supported a relevant abstract hypothesis that proved sufficient to establish global stability of the solution. We have since completed a full mathematically-rigorous study of a piecewise affine version of this model, establishing all of the observed phenomenology (both existence and stability of TW) analytically. In addition, we now have an understanding of how a robust TW solution in this setting may be generated with a variety of external forcing stimuli, including such that are structurally distinct from the consequent wave. This is an apparent feature of this class of models.

Stanislav M. Mintchev
The Cooper Union
New York
mintchev@cooper.edu

Bastien Fernandez
Laboratoire de Probabilités et Modèles Aléatoires
CNRS - Université Paris Diderot - UPMC
bastien.fernandez@lpma-paris.fr

MS73

Hidden Symmetry in Coupled Cell Networks

Dynamical systems with a network structure often display remarkable similarities with equivariant systems (that is, systems possessing a symmetry). For example, a network structure often seems to force the existence of flow-invariant subspaces, and the linearized system on such a space often comes with a degenerate spectrum. As a result, many network ODE's support generic bifurcations that are unheard of for general vector fields (a phenomenon that is again well-known for symmetric systems). We present a set-up where network ODE's are indeed presented as (subsystems of) symmetric systems. This in turn yields relatively straightforward explanations for the aforementioned phenomena, most notably by the formulation of a center manifold theorem for networks. An interesting caveat is the fact that these symmetries seldom come from groups, but rather from monoids and other algebraic structures. This opens the door to very interesting generalizations of equivariant dynamics and representation theory.

Eddie Nijholt, Bob Rink
VU University Amsterdam
eddie.nijholt@gmail.com, b.w.rink@vu.nl

Jan Sanders
Free University of Amsterdam
Tne Netherlands
jansa@cs.vu.nl

MS73

Maps Coupled in Networks. The Interplay Between Structure and Dynamics

Recent results reveal that typical real-world networks have various levels of connectivity. These networks exhibit emergent behaviour at various levels. For instant, massively connected nodes can synchronise, while less connected nodes do not. Striking examples are found in the brain, where synchronisation between highly connected neurons coordinate and shape the network development. These phenomena remain a major challenge. We will discuss consider expanding maps coupled on networks with various connectivity scales and perform a probabilistic dimension reduction to describe the network dynamics. We show that, at large levels of connectivity, the high-dimensional network dynamics can be reduced to a few macroscopic equations. This reduction provides the opportunity to explore the coherent properties at various network connectivity scales. This is a join work with M. Tanzi and S. van Strien.

Tiago Pereira
ICMC-University of Sao Paulo
Sao Carlos
tiago@icmc.usp.br

MS74

A Model for Diffusive Gas Dynamics Away from Thermodynamic Equilibrium

We find that the Boltzmann equation is a simplification of a multimolecular random jump system, which is different from the realistic gas dynamics. We correct the difference via a multiscale homogenization formalism, which equips the Boltzmann equation and its fluid dynamics closures with a spatial diffusion term. As a result, the nonequilibrium Grad closure becomes well posed for boundary value problems, and can be used for practical problems in the same manner as the Navier-Stokes equations. For the Couette flow, we find that the diffusive Grad closure captures both the Knudsen boundary layer and the nonzero heat flux in the direction of the flow.

Rafail Abramov
Department of Mathematics, Statistics and Computer Science
University of Illinois at Chicago
abramov@uic.edu

MS74

Dynamics of Optical Pulses Riding on a Back-

ground, An Exact Approach

The study of scalar and vector nonlinear Schrödinger (NLS) and Maxwell-Bloch (MB) systems with non-zero boundary conditions at infinity has received renewed interest recently. This talk will report on recent results on focusing scalar and vector NLS and MB equations with non-zero boundary conditions. It will be shown how the inverse scattering transform can be constructed in both cases, and a number of explicit soliton solutions will be discussed.

Gregor Kovacic
Rensselaer Polytechnic Inst
Dept of Mathematical Sciences
kovacg@rpi.edu

Gino Biondini
State University of New York at Buffalo
Department of Mathematics
biondini@buffalo.edu

Daniel Kraus
SUNY Buffalo
dkkraus@buffalo.edu

Sitai Li
State University of New York at Buffalo
sitaili@buffalo.edu

Ildar R. Gabitov
Department of Mathematics, University of Arizona
gabitov@math.arizona.edu

MS74

An Openfoam Implementation of the Nonequilibrium Diffusive Gas Dynamics Model: Testing and Validation

We implement a novel scheme in the high-level finite-volume description defined in OpenFOAM atop C++, thus abstracting over a rich variety of meshes and boundary conditions with guaranteed physical units. We discuss the procedure to define and compile the custom solver, and demonstrate a low-abstraction open-source toolchain to define and analyze standard compressible flow problems against multiple solvers.

Jasmine T. Otto
Department of Mathematics, Statistics and Computer Science
University of Illinois at Chicago
jotto3@uic.edu

MS74

Effective Dispersion and Linearization in Wave-Like Systems

Effective dispersion in extended systems may be generated by the increasing nonlinearity, with resonant wave-wave interactions appearing or disappearing, and resonant manifolds deforming. This occurs even in systems with no linear dispersion. In such a subcase of the MMT model, due to its symmetry, we calculated energy and wavenumber spectra both directly and from the wave-turbulence theory associated with the effective dispersion relation. For the NLS equation, we computed this relation to be a quadratic.

Madison Wyatt, Katelyn J. Leisman, Michael Schwarz
Rensselaer Polytechnic Institute
wyattm@rpi.edu, plaisk@rpi.edu,
mschwarz137@gmail.com

Peter R. Kramer
Rensselaer Polytechnic Institute
Department of Mathematical Sciences
kramep@rpi.edu

Gregor Kovacic
Rensselaer Polytechnic Inst
Dept of Mathematical Sciences
kovacg@rpi.edu

David Ca
Shanghai Jiao Tong University, China,
Courant Institute, New York University, USA.
cai@cims.nyu.edu

Maxwell Jenquin, Alexander Mayer
Rensselaer Polytechnic Institute
jenqum@rpi.edu, mayera2@rpi.edu

MS75

Bellerophon States: Coexistence of Quantized, Time Dependent, Clusters in Globally Coupled Oscillators

From rhythmic physiological processes to the collective behaviors of technological and natural networks, coherent phases of interacting oscillators are the foundation for the emergence of the system's cooperative functioning. We unveil the existence of a new of such states, occurring in globally coupled nonidentical oscillators in the proximity of the point where the transition from the system's incoherent to coherent phase converts from explosive to continuous. In such a state, oscillators form quantized clusters, where they are neither phase- nor frequency-locked. Oscillators' instantaneous speeds are different within the clusters, but they form a characteristic cusped pattern and, more importantly, they behave periodically in time so that their average values are the same. Given its intrinsic specular nature with respect to the Chimera states, the phase is termed the Bellerophon state. We provide analytical and numerical description of the microscopic and macroscopic details of Bellerophon states, thus furnishing practical hints on how to seek for the new phase in a variety of experimental and natural systems.

Hongjie Bi
Department of Physics, East China Normal University, Shangha
bihongjie19861986@163.com

Xin Hu
Key Lab of Nanodevices and Applications-CAS
Chinese Academy of Sciences, Suzhou 215123, China
460758419@qq.com

Stefano Boccaletti
CNR-Istituto dei Sistemi Complessi
stefano.boccaletti@isc.cnr.it

Xingang Wang
Zhejiang University, China
wangxg@snnu.edu.cn

Yong Zou, Zonghua Liu, Shuguang Guan

East China Normal University, Shanghai 200241, China
yzou@phy.ecnu.edu.cn, zhliu@phy.ecnu.edu.cn, guanshuguang@hotmail.com

MS75

Anomalous Critical and Supercritical Phenomena in Explosive Percolation

The emergence of large-scale connectivity on an underlying network or lattice, the so-called percolation transition, has a profound impact on the systems macroscopic behaviors. There is thus great interest in controlling the location of the percolation transition to either enhance or delay its onset and, more generally, in understanding the consequences of such control interventions. Here we review explosive percolation, the sudden emergence of large-scale connectivity that results from repeated, small interventions designed to delay the percolation transition. These transitions exhibit drastic, unanticipated and exciting consequences that make explosive percolation an emerging paradigm for modelling real-world systems ranging from social networks to nanotubes.

Raissa D'Souza
UC Davis
raissa@cse.ucdavis.edu

MS75

Recent Advances in Explosive Percolations and their Applications

Percolation has long served as a model for diverse phenomena and systems. The percolation transition, that is, the formation of a giant cluster on a macroscopic scale, is known as one of the most robust continuous transitions. Recently, however, many abrupt percolation transitions have been observed in complex systems. To illustrate such phenomena, considerable effort has been made to introduce models and to construct theoretical frameworks for explosive, discontinuous, and hybrid percolation transitions. Experimental results have also been reported. In my talk, I will review results of such effots, percolation models, their critical behaviors and universal features, and real-world phenomena.

Byungnam Kahng
Department of Physics and Astronomy
Seoul National University
bkahng@snu.ac.kr

MS75

Mechanism of Explosive Synchronization in Networked Oscillators

In the past several years, explosive synchronization in networked oscillators has became a hot topic. Many models and aspects of explosive synchronization have been studied. In our work, we focus on the mechanism of explosive synchronization and find a mechanism called "suppress rule" which is similar to the mechanism of explosive percolation. Taking advantage of this "suppress rule", we can generate explosive synchronization in different kinds of network (fully connected, random, scale free and multi-layer network). Through the further research, we find other mechanism (such as competition) can also lead to explosive synchronization. In my talk, I will introduce the mechanisms of explosive synchronization we found.

Xiyun Zhang
Keck Laboratory for Network Physiology
Physics Department, Boston University
zxy822@bu.edu

MS76

Speed Modulated Social Influence in Evacuating Pedestrian Crowds

Models of pedestrian motion such as the social force model and the anticipatory collision avoidance model are often validated in terms of their ability to faithfully reproduce an evacuation situation, where individuals exit a confined space through a single exit. Most pedestrian models are able to reproduce salient features of pedestrian evacuation such as the faster-is-slower effect, which represents the significantly longer time taken by a rushing crowd to evacuate than a crowd which is relatively less hurried. The social influence in such models is represented in the form of a repelling action based on proximity or time-to-collision, and all individual agents are modeled to have the same tendency to exit. We show through experiments that in scenarios where individuals may have different tendencies to exit, difference in speed exerts an additional social influence. Specifically, we analyze trajectory data of crowds of individuals with different tendencies to exit and show the presence of social influence where slower individuals tend to speed up in the presence of those that are rushing. These results motivate an update to pedestrian motion models in order to include social influence due to variability in speeds.

Sachit Butail
Northern Illinois University
sbutail@niu.edu

Abhishek Bhatia
Indian Institute of Technology Delhi
abhigenie92@gmail.com

Elham Mohammadi
Northern Illinois University
z1807010@students.niu.edu

MS76

Lagrangian Coherent Structures as Sub-mesoscale Transport Barriers in Amospheric Flows

Lagrangian coherent structures (LCS) in two-dimensional flows have been studied in the context of transport in fluid dynamics. However, for geophysical systems a small vertical velocity can lead to nontrivial three-dimensional motion of airborne particles. Examples of such particles include biological populations affecting agriculture and hazardous outputs from both man-made and natural disasters. The pathways and barriers in the lower atmosphere, from ground level to a kilometer altitude and over a horizontal scale of several kilometers–which bridges the scale of, for example, local terrain to the larger regional scale–are still unclear. This requires exploring relevant spatiotemporal scales related to advection in the space of 3D + time. In this talk, we will present the application of finite-time Lyapunov exponent-based three-dimensional LCS to address questions of transport using historical data sets from satellite observations, local field measurements and the Weather Research and Forecasting (WRF) model.

Peter Nolan
Virginia Polytechnic Institute and State University

pnolan86@vt.edu

MS76

Interactional Dynamics of Same-Sex Marriage Legislation in the United States

Understanding how people form opinions and make decisions, at individual and population scales, is a complex phenomenon that depends on both personal practices and interactions with others. Recent availability of real-world data has enabled opinion formation analysis, which can shed light on phenomena that impact physical and social sciences. Public policies exemplify complex opinion formation spanning individual and population scales, and a timely example is the legalization of same-sex marriage in the United States. Here, we seek to understand how this issue captures the relationship between state laws and Senate representatives as it depends on geographic and ideological factors. Using a distance-based correlation metric, we study how physical proximity and state-government ideology may be used to extract patterns in state-law adoption and senatorial support of same-sex marriage. Results demonstrate that proximal states have a strong similarity in both the state-law and the senators' opinions, and states with similar state-government ideology are predictors of the senators' opinions. Moreover, we find from a time-lagged correlation that state-laws show maximum dependencies on senators' opinions from one year prior. Thus, change in opinion is not only a result of negotiations among the individuals, but also reflects inherent spatial and political similarities. We build a social impact model of state-law adoption in light of these results and verify its predictive power.

Subhradeep Roy, Nicole Abaid
Virginia Polytechnic Institute and State University
sdroy@vt.edu, nabaid@vt.edu

MS76

A Persistent Homology Approach Towards a Thermodynamic Description of Insect Swarms

Various animals from birds and fish to insects tend to form aggregates, displaying self-organized collective swarming behavior. Due to their frequent occurrence in nature and their implications for engineered, collective systems, these systems have been investigated and modeled thoroughly for decades. Common approaches range from modeling them with coupled differential equations on the individual level up to continuum approaches. We present an alternative, topology-based approach for describing swarming behavior at the macroscale rather than the microscale. We study laboratory swarms of Chironomus riparius, a flying, non-biting midge. To obtain the time-resolved three-dimensional trajectories of individual insects, we use a multi-camera stereoimaging and particle-tracking setup. To investigate the swarming behavior in a topological sense, we employ a persistent homology approach to identify persisting structures and features in the insect swarm that elude a direct, ensemble-averaging approach. We are able to identify features of sub-clusters in the swarm that show behavior distinct from that of the remaining swarm members. The coexistence of sub-swarms with different features resembles some non-biological systems such as active colloids or even thermodynamic systems.

Michael Sinhuber, Nicholas T. Ouellette
Stanford University
sinhuber@stanford.edu, nto@stanford.edu

MS77

On How Turing Triggers Biochemical Spot Dynamics in a Plant Root Hair Initiation Model

Pattern formation aspects in a 2D reaction-diffusion (RD) sub-cellular model characterising the effect of a spatial gradient of a plant hormone distribution on a family of G-proteins associated with root-hair (RH) initiation in the plant cell Arabidopsis thaliana are analysed. The activation of these G-proteins, known as the Rho of Plants (ROPs), by the plant hormone, auxin, is known to promote certain protuberances on root hair cells, which are crucial for both anchorage and the uptake of nutrients from the soil. The mathematical model for the activation of ROPs by the auxin gradient is an extension of the model proposed by Payne and Grierson [PLoS ONE, 12(4), (2009)], and consists of a two-component generalised Schnakenberg RD system with spatially heterogeneous coefficients on a 2D domain. The components in this system model the spatio-temporal dynamics of the active and inactive forms of ROPs. As will be shown, Turing bifurcation plays a key role on the triggering phenomenon that gives place to such a localised structures. By using a singular perturbation analysis to study 2D localised spatial patterns of active ROPs, it is shown that the spatial variations in the model, due to the auxin gradient, lead to a slow spatial alignment of the localised regions of active ROPs along the midline of the plant cell.

Victor F. Brena-Medina
Universidad Nacional Autonoma de Mexico
University of Bristol
victorb@matmor.unam.mx

Michael Ward
Department of Mathematics
University of British Columbia
ward@math.ubc.ca

MS77

After 1952: Alan Turing's Later Work on Pattern Formation

Alan Turing's paper 'The chemical basis of morphogenesis' [*Phil. Trans. R. Soc. Lond.* B **237**, 37–72 (1952)] remains hugely influential despite being his only published work in the field of mathematical biology. In this talk I will discuss the later development of his ideas as revealed by lesser-known, but readily available, archive material. This material shows that Turing studied differential equation models (motivated by various biological phenomena including phyllotaxis and the unicellular marine organisms *Radiolaria*) that present a significantly more complicated mathematical challenge than the well-known analysis contained in the 1952 paper. In taking on this challenge, Turing's work anticipates (i) the description of patterns in terms of modes in Fourier space and their nonlinear interactions, (ii) the construction of the well-known model equation usually ascribed to Swift & Hohenberg, published 23 years after Turing's death, and (iii) the use of symmetry to organise computations of the stability of symmetrical equilibria corresponding to spatial patterns. It is also notable that Turing's later work appears to have been carried out separately from, and in parallel with, related developments in fluid mechanics.

Jonathan Dawes

University of Bath
J.H.P.Dawes@bath.ac.uk

MS77

Patterns in the Starch-Iodine Reaction

The reaction between starch and iodine has interested people since 1812, including a young chemically intrigued Alan Turing. The interaction of iodine vapor with a starch solution can produce a variety of patterns such as stripes and hexagons. A model to explain this reaction which makes use of the cooperative binding of iodine molecules to the starch helix will be presented.

Derek Handwerk
Colorado State University
handwerk@math.colostate.edu

MS77

Phyllotaxis: The Hows Rather Than the Whys

Phyllotaxis, the arrangement of phylla, leaves, flowers, florets, bracts, on the shoot apical meristems (SAMS) of plants has mystified and fascinated natural scientists for more than two thousand years. Recently there has been considerable progress in understanding the observed behaviors. This talk will review the progress in understanding what the biochemical processes are which give rise to what is seen and will contrast the results with those obtained by teleological approaches based on the idea that plants organize their SAMS to optimize access to light and/or nutrients. What is remarkable is that in many respects both approaches lead to similar patterns which suggests that perhaps in many contexts nature uses pattern forming processes to achieve optimal outcomes.

Alan Newell
University of Arizona
Department of Mathematics
anewell@math.arizona.edu

MS78

Combinatorial Approximation and Discrete-Time Dynamics

Researchers have used Conley index theory as a base for computer-assisted proof techniques for dynamical systems. In this talk, we will explore some recent work in automating approaches for uncovering highly complicated, often chaotic, dynamics in discrete-time systems governed by iterated maps. I will also briefly discuss challenges in extending these techniques to systems described solely by time series measurements and give sample computations for illustration.

Sarah Day
The College of William and Mary
sday@math.wm.edu

MS78

Classification of Pattern-Forming Systems Using Persistence

Complex spatial-temporal patterns can be difficult to characterize quantitatively, but examples of such patterns are ubiquitous. For example, the anisotropic Kuromoto-Sivashinky equation which has been derived to model pattern-forming systems driven far from equilibrium in a wide array of applications. In seeking to understand the mechanisms of pattern formation, studying the effect of parameters on the formation and evolution of complex spatio-temporal patterns offers valuable insight into underlying mechanisms driving the system. However, determining these parameters can be difficult and computationally expensive. We believe that the parameters influence the dynamic data in a way that is detectable by persistent homology. Using a finite-dimensional vector representation of persistence diagrams called persistence images, we are able to leverage machine learning techniques to classify data by parameters and to consider the temporal evolution of the pattern. The reduction of the dynamic data using persistent homology still retains a remarkable amount of information that is useful for parameter classification and we are able to achieve good classification results for simulated data.

Rachel Neville
Colorado State University
neville@math.colostate.edu

Patrick Shipman
Department of Mathematics
Colorado State University
shipman@math.colostate.edu

MS78

Witness Complexes for Time Series Analysis

A scalar time-series can be “unfolded” into $\mathbb{R}^d$ by delay coordinate reconstruction. In the best case, this gives an attractor that is topologically equivalent to that of the underlying dynamical system. We can then compute the persistent homology of the data using a variety of complexes, e.g., Čech, Vietoris-Rips, or alpha. To be more computationally efficient we use a witness complex: it can provide a sparser representation and yet be faithful to the homology. Topologically accurate delay reconstruction requires choice of appropriate values for a d and a time delay. In practice, these must be estimated from the data, and the estimation procedures are heuristic and often problematic. Recent work of Garland et al. demonstrates that accurate persistent homology computations are possible from witness complexes built from delay reconstructions with d below that demanded by the theory. Following this, we introduce novel witness relations that incorporate time and explore the robustness of the resulting homology with respect to choice of delay. We utilize the witness map, a multivalued map on the witness complex induced by the temporal ordering of the data and velocity estimates. The new relations seek to inhibit data points from witnessing landmarks traveling in disparate directions and that are on distinct branches of an attractor, as these can suggest a false connection, due to the particular reconstruction.

Nicole Sanderson
University of Colorado
Department of Mathematics
nicole.sanderson@colorado.edu

MS78

Topological Data Analysis of Stochastic Collective Motion

We introduce computational persistent homology, the workhorse of topological data analysis, to a dynamical systems audience. Then, we apply this tool to analyze a seminal model of collective motion due to Vicsek et al. (1995).

The model describes an ensemble of self-driven particles. At each moment, each particle's heading is determined by interactions with neighbors, subject to noise. Using time series of the particles' positions and headings, we assign a topological signature to the evolving ensemble. This signature identifies dynamical events that traditional methods do not. Finally, we pose open questions related to topological signatures averaged over many simulations of the noisy model. No previous knowledge of topology is required.

Chad M. Topaz
Dept. of Mathematics, Statistics, and Computer Science
Macalester College
ctopaz@macalester.edu

MS79

Extensions of Koopman Operator Theory: Stochastic Dynamical Systems and Partial Differential Equations

We extend the theory of Koopman operators to the case of random dynamical systems. We show that the stochastic Koopman operator for random linear systems, defined using expectation over the state space of the underlying random process, admits eigenfunctions related to expectation of eigenvectors of the system. We use this to, via conjugacy, provide a theory for a large class of random dynamical systems. We also describe an extension of the Koopman operator theory for partial differential equations, where we define the notion of eigenfunctionals of the Koopman operator and describe consequences for reduced order modeling of the dynamics.

Igor Mezic
University of California, Santa Barbara
mezic@engineering.ucsb.edu

MS79

Reconstruction of the Koopman Operator's Spectral Measure from Data

In data-driven modeling using the Koopman operator, it is often implicitly assumed that the operator either has a pure point spectrum or the observables under consideration are in the span of the operator's eigenfunctions. In this talk, we discuss methods of reconstructing the operator's spectral measure from data with an emphasis on the continuous part of the spectrum.

Ryan Mohr
University of California, Santa Barbara
mohrrm@engineering.ucsb.edu

MS79

Manifold Learning with Contracting Observers for Data-Driven Dynamical Systems Analysis

High dimensional signals generated by dynamical systems arise in many fields of science. For example, many biomedical signals can be modeled by few latent physiologically-related variables measured by a large set of noisy sensors. In such applications the goal is to identify the latent intrinsic variables, which describe the true, intrinsic state of the system. We approach the problem from a geometric analysis standpoint by applying manifold learning. Our main assumption is that the accessible high dimensional data (the observations of the system) lie on an underlying nonlinear manifold of lower dimensions. We present a purely data-driven framework in which, first, an intrinsic representation is derived without prior knowledge on the system by applying diffusion maps. Second, we show that the dynamics of the constructed representation are approximately linear, even for highly non-linear systems, and propose two filtering frameworks based on a linear observer and based on the Kalman filter. These filtering schemes enable to incorporate the inherent dynamics and time dependencies between consecutive system observations into the diffusion maps coordinates. We demonstrate the benefits of our approach on simulated data and on real recordings from various applications.

Tal Shnitzer, Ronen Talmon
Technion
shnitzer@tx.technion.ac.il, ronen@ee.technion.ac.il

Jean-Jacques Slotine
MIT
jjs@mit.edu

MS80

Noise-induced Transitions between Alternative Stable Periodic Orbits of a Periodically-forced System: Is there a Preferred Phase for Tipping?

We consider a simple periodically-forced 1-D Langevin equation which possesses two stable periodic orbits in the absence of noise. We ask the question: is there a preferred phase of the periodic-forcing and a most likely transition path between the stable orbits? The question arose in the setting of a conceptual Arctic sea ice model in a bistable region, where we were interested in whether it is more vulnerable to noise in the winter or summer. We compare results for our model problem obtained in three different ways: (1) calculating statistics of the tipping time obtained from path-wise analysis, (2) computing optimal transition path using a least-action principle, and (3) examining features of the steady state solution of the associated Fokker Planck equation for the probability density. Results for the preferred tipping phase are compared with the deterministic aspects of the problem, and interpreted for the Arctic sea ice model.

Yuxin Chen
Northwestern University
yuxinchen2018@u.northwestern.edu

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

John Gemmer
Wake Forest University
Department of Mathematics
gemmerj@wfu.edu

Alexandria Volkening
Division of Applied Mathematics
Brown University
alexandria_volkening@brown.edu

MS80

Sequential Escapes for Network Dynamics

It is well known that the addition of noise in a multistable system can induce random transitions between stable states. Analysis of the transient dynamics responsible for these transitions is crucial to understanding, for example, the evolution of epileptic seizures. We consider sequential transitions, also called escapes, of nodes in directed networks. We assume that each node has two stable states, one of which is only marginally stable. All nodes start in this marginally stable state and once a node has escaped we assume that the transition times back are astronomically large by comparison. Using numerical and theoretical techniques we explore how escape times of the network are effected by changes in network structure, noise amplitude and coupling strength.

Jennifer L. Creaser
The University of Exeter
Centre for Predictive Modelling in Healthcare
j.creaser@exeter.ac.uk

Jennifer L. Creaser
University of Exeter, UK
EPSRC Centre for Predictive Modelling in Healthcare
j.creaser@exeter.ac.uk

Peter Ashwin
University of Exeter, UK
p.ashwin@exeter.ac.uk

Krasimira Tsaneva-Atanasova
University of Exeter
k.tsaneva-atanasova@exeter.ac.uk

MS80

Rate-Induced Tipping Through Hopf Bifurcations in Fast/Slow Systems

We analyze rate-dependent tipping in a fast/slow system. In the reduced co-moving system we find a Hopf bifurcation as the rate parameter increases. This implies extra structure as the system moves from tracking a quasi-static equilibrium to tipping, and poses new questions about what defines a tipping point. In this kind of rate-induced tipping phenomenon, the state tracks the quasi-static equilibrium in a spiral corresponding to the emerging periodic orbit in the Hopf bifurcation of the reduced system.

Jonathan Hahn
University of Minnesota
hahnx240@umn.edu

MS80

Non Smooth Tipping from Paleoclimate

A recently-developed conceptual climate model incorporating Earth's energy balance, ice-albedo feedback, and the mass-balance principle has been shown to exhibit limit cycles reminiscent of glacial cycles. The model is nonsmooth with a "switch" that is activated when the ice mass balance reaches a certain threshold. In this talk, I will present the model, the tipping behavior that leads to large oscillations, and I will discuss its physical interpretation.

Esther Widiasih
Mathematics and Science Subdivision
University of Hawaiʻi West Oʻahu
widiasih@hawaii.edu

MS81

Spatio-temporal Canards in Neural Field Models

Canards are special solutions to ordinary differential equations that follow invariant repelling slow manifolds for long time intervals. In realistic biophysical single cell models, canards are responsible for several complex neural rhythms observed experimentally, but their existence and role in spatially-extended systems is largely unexplored. We describe a novel type of coherent structure in which a spatial pattern displays temporal canard behaviour. Using interfacial dynamics and geometric singular perturbation theory, we classify spatio-temporal canards and give conditions for the existence of folded-saddle and folded-node canards. We find that spatio-temporal canards are robust to changes in the synaptic connectivity and firing rate. The theory correctly predicts the existence of spatio-temporal canards with octahedral symmetries in a neural field model posed on the unit sphere. This is joint work Mathieu Desroches and Edgar Knobloch.

Daniele Avitabile
School of Mathematical Sciences
University of Nottingham
Daniele.Avitabile@nottingham.ac.uk

MS81

A Robust Neural Integrator Based on the Interactions of Three Time Scales

Abstract Not Available At Time Of Publication.

Bard Ermentrout
University of Pittsburgh
Department of Mathematics
bard@pitt.edu

MS81

Ducks in Space: From Nonlinear Absolute Instability to Noise-sustained Structures

A subcritical pattern-forming system with nonlinear advection in a bounded domain is recast as a slow-fast system in space and studied using a combination of geometric singular perturbation theory and numerical continuation. Two types of solutions describing the possible location of stationary fronts are identified, one of which is present for all values of the bifurcation parameter while the other is present for zero or sufficiently small inlet boundary conditions but only when the bifurcation parameter is large enough. For slightly larger inlet boundary condition a continuous transition from one type to the other takes place as the bifurcation parameter increases. The origin of the two solution types is traced to the onset of convective and absolute instability on the real line. The role of canard trajectories in the transitions between these states is clarified and the stability properties of the resulting spatial structures are determined. Front location in the convective regime is highly sensitive to the upstream boundary condition and its dependence on this boundary condition is studied using a combination of numerical continuation and Monte Carlo simulations of the partial differential equation. Statistical properties of the system subjected to random or stochastic boundary conditions at the inlet are interpreted using the deterministic slow-fast spatial-dynamical system. This is joint work with D. Avitabile, M. Desroches and M. Krupa.

Edgar Knobloch
University of California, Berkeley -
Nonlinearity, Institute of Physics
knobloch@berkeley.edu

MS81

Role of Gap Junctions in a Neuron Astrocyte Network Model

A detailed biophysical model for a neuron/astrocyte network is developed to explore mechanisms responsible for the initiation and propagation of cortical spreading depolarizations and the role of astrocytes in maintaining ion homeostasis, thereby preventing these pathological waves. In particular, we consider the neuroprotective role of astrocyte gap junction coupling. The model demonstrates that a syncytium of electrically coupled astrocytes can maintain a physiological membrane potential in the presence of an elevated extracellular potassium concentration and efficiently distribute the excess potassium across the syncytium. This provides an effective mechanism for delaying or preventing the initiation of spreading depolarizations.

David H. Terman
The Ohio State University
Department of Mathematics
terman@math.ohio-state.edu

MS82

Skipping a Pill to Prevent Drug Resistance?

The antiviral drug oseltamivir has proven very effective in reducing influenza symptom intensity and accelerating recovery. However oseltamivir's utility can be compromised by the emergence of drug resistant strains. We employ a hybrid deterministic and stochastic simulation model which combines models of drug pharmacokinetics, pharmacodynamics, viral kinetics and immune responses to investigate oseltamivir use accross a distribution of patient types. Via simulation, we investigate the interplay between drug efficacy and innate immune responses that can prevent or accelerate emergence of drug resistant strains. Treatment regimen initiation during the incubation period is typically found to be the main factor leading to resistance emergence in a patient: resistant strains are selected when treatment is too late to prevent *de novo* mutation to a drug resistant variant, but still early enough to suppress development of immune responses that would control both drug sensitive and drug resistant strains. Thus, although conventional wisdom says improper use of antivirals, including dose skipping, leads to drug resistance, skipping a dose may actually reduce probability of emergent drug resistance by allowing for immune response development. We will explore non-traditional treatment regimens aimed at maximizing treatment effectiveness while minimizing the risk of drug resistance emergence.

Jessica M. Conway
Pennsylvania State University
jmconway@psu.edu

MS82

Modeling Combination Therapies Using Latency Reversing Agents and Immunotherapeutics to Cure Hiv

The existence of latent reservoir, a population of cells latently infected by HIV, is a major barrier to cure HIV infection. Extensive efforts have focused on shock and kill strategies to purge the latent reservoir. The idea is to shock the latently infected cells using latency reversing agents (LRAs) to activate HIV gene expression, and then these cells can be killed rapidly via viral cytopathic effects or immune-mediated cell death. Here, we focus on the combination therapies involving both LRAs and immunotherapeutics that active HIV expression in latently infected cells and boost immune-mediated killing to purge the reservoir. We construct mathematical models to describes the dynamics of latently infected cells under the combination therapies. We show that in addition to shock and kill rates, a previously understudied parameter, the length of time that HIV antigen is expressed and can be recognized by immune effector cells, plays an important role in determining the efficacy of HIV latency reversal strategies. Therefore, in addition to increasing shock and kill rates, drug development should focus on drugs that maximize the duration of HIV expression and antigen presentation both during and after treatment. We further estimate the potential efficacy of a recently developed immune-therapeutics based on the Dual-Affinity Re-Targeting proteins based on experimental data, and develop treatment strategies based on the characteristics of the therapeutics.

Ruian Ke
North Carolina State University
ruian_ke@ncsu.edu

MS82

Impact of Innate Immune Response on Spatial Dynamics of Acute In-host Viral Infection

The innate immune response, particularly interferon production and signaling, represents the first line of defense against viral invasions. Previously, in-host viral dynamics and the innate immune response have been studied mostly as a spatially homogeneous system. Though valid for some diseases and tissue types, this assumption of homogeneous mixing ignores the biological reality of the spatial distribution of cells and diffusion of viruses and interferon molecules in an organ or epithelium for many other viral systems.

Michael Lavigne, Hayley Russell, Ruian Ke
North Carolina State University
gmlavign@ncsu.edu, n/a, ruian_ke@ncsu.edu

MS82

Targeting the Achilles Heel of HIV Reservoir Persistence

HIV cure remains elusive due to a reservoir of latently infected memory CD4+ T-cells which persist despite decades of antiretroviral therapy (ART). Using mathematical model fit to existing data, we demonstrate that after one year of ART, most reservoir cells are generated via proliferation rather than new viral infection. We discuss methods to differentiate the percentage of proliferation events which are antigen driven rather than programmed homeostasis among different reservoir T cell subsets. We conclude by modeling antiproliferative therapy as a means to reduce reservoir volume.

Joshua Schiffer
Fred Hutchinson Cancer Research Center

jschiffe@fredhutch.org

MS83

Cardiac Re-Entry Evolution in MRI-based Models of the Heart

Despite over a century of study, mechanisms of cardiac arrhythmias are poorly understood. The recently discovered new phenomenon of dissipative vortices interaction with sharp variations of thickness in excitable layer suggests a cardiac re-entry interaction with fine anatomical features such as pectinate muscles and terminal crest in atria, which might cause considerable displacement of the re-entry's established localisation compared to where it was first initiated. With the recent advance in DT-MRI technology, more detailed models of heart anatomy are becoming available for inclusion into anatomically realistic computer simulations of cardiac arrhythmias, providing a fascinating in-silico test bed with unimpeded access to the whole heart at greater spatial and temporal resolutions than in experiment, to test the effects of a patient anatomy on cardiac re-entry dynamics.

Irina Biktasheva
University of Liverpool
ivb@liv.ac.uk

Vadim N. Biktashev
College of Engineering, Mathematics and Physical Sciences
University of Exeter
V.N.Biktashev@exeter.ac.uk

Arun Holden
University of Leeds, UK
a.v.holden@leeds.ac.uk

Sanjay R. Kharche
University of Exeter
s.r.kharche@exeter.ac.uk

Eleftheria Pervolaraki
University of Leeds, UK
fbsepe@leeds.ac.uk

Girish Ramlugun
Auckland BioEngineering Institute, Auckland, New Zealand
girish.ramlugun@auckland.ac.nz

Gunnar Seemann
Karlsruhe Institute of Technology
Germany
gunnar.seemann@kit.edu

Bruce smaill
Auckland BioEngineering Institute, Auckland, New Zealand
b.smaill@auckland.ac.nz

MS83

Incorporating Data into Models of Cardiac Electrical Dynamics

Cardiac tissue displays a broad range of dynamical behaviors, including bifurcations and spiral and scroll waves of electrical activity. However, understanding experimental results is challenging because complex behavior can occur in the tissue depth, but measurements are restricted primarily to the tissue surfaces. We will discuss recent advances in using data assimilation to use observations sparse in time and space to reconstruct cardiac electrical dynamics. We show ways of handling discrepancies between the dynamics of the observed system and the numerical model used, including parameter value differences, dissimilar wave shapes, and spatial heterogeneity in the observed system. In addition, we will discuss how observations can be used to estimate parameter values and show results in the cardiac setting.

Elizabeth M. Cherry
Rochester Institute of Technology
School of Mathematical Sciences
excsma@rit.edu

Darby Cairns
Rochester Institute of Technology
dic4597@rit.edu

Nicholas LaVigne
Cornell University
nsl42@cornell.edu

Nathan Holt
Rochester Institute of Technology
nxh7119@mail.rit.edu

Flavio H. Fenton
Georgia Institute of Technology
flavio.fenton@physics.gatech.edu

Matthew J. Hoffman
Rochester Institute of Technology
mjhsma@rit.edu

MS83

Reconstruction of Cardiac Dynamics from Cardiac Deformation Mechanics

The self-organizing, dynamic pattern forming processes that underlie the arrhythmic electrical activity during cardiac fibrillation remain insufficiently understood due to the absence of requisite in-depth imaging techniques, capable of visualizing the fibrillatory electrical patterns throughout the volume of the cardiac muscle. Here, we show that intracardiac wave phenomena can be reconstructed by imaging and analyzing the fibrillatory contractile deformation mechanics of the cardiac muscle. Combining optical mapping, ultrasound and computational modeling, we show that the arrhythmic electromechanical activity of the heart exhibits closely correlated electrical and mechanical dynamics. During fibrillation in isolated hearts, we observed that electrical spiral wave rotors can be accompanied by rotational elasto-mechancial patterns, which like fingerprints of vortex activity depict characteristic dynamic properties of fibrillation and reveal the underlying structural organization of the wave dynamics evolving inside the cardiac muscle. In summary, three-dimensional cardiac deformation mechanics can reveal elasto-mechanical topological defect lines or lines of mechanical phase singularity, which reflect vortex wave dynamics such as scroll wave activity. In particular, the combination of the imaging data with computational modeling of cardiac electromechanics can provide solutions to the inverse problem in which electrical wave phenomena are computed from mechanical deformation.

Jan Christoph, Stefan Luther
Max Planck Institute for Dynamics and Self-Organization
Research Group Biomedical Physics
jan.christoph@ds.mpg.de, stefan.luther@ds.mpg.de

MS83

Cardiac Response to Low-Energy Field Pacing Challenges the Standard Theory of Defibrillation

The electrical response of myocardial tissue to periodic field stimuli has been considered as the basis for low-energy anti-fibrillation pacing (LEAP), potentially more effective than traditional single high-energy shocks. In conventional models, an electric field produces a highly non-uniform response of the myocardial wall, with discrete excitations, or hot spots (HS), occurring at cathodal tissue surfaces or large coronary vessels. We test this prediction using novel 3D tomographic optical imaging. Experiments were performed in pig ventricular wall stained with near-infrared voltage-sensitive fluorescent dye DI-4-ANBDQBS. The 3D coordinates of HS were determined using alternating transillumination. The peak HS distribution is located deep inside the heart wall and the depth is not significantly affected by field polarity. We did not observe the strong colocalization of HS with major coronary vessels anticipated from theory. Yet, we observed considerable lateral displacement of HS with field polarity reversal. Models that deemphasized lateral intracellular coupling and accounted for resistive heterogeneity in the extracellular space showed similar HS distributions to the experimental observations. The HS distributions within the myocardial wall and the significant lateral displacements with field polarity reversal are inconsistent with standard theories of defibrillation. Extended theories based around ephaptic mechanisms may be necessary.

Arkady Pertsov
SUNY Upstate Medical University
pertsova@upstate.edu

MS84

Bistable Gaits and Wobbling Induced by Pedestrian-Bridge Interactions

Several modern footbridges around the world have experienced large lateral vibrations during crowd loading events. The onset of large-amplitude bridge wobbling has generally been attributed to crowd synchrony; although, its role in the initiation of wobbling has been challenged. To study the contribution of a single pedestrian into overall, possibly unsynchronized, crowd dynamics, we use a bio-mechanically inspired inverted pendulum model of human balance and analyze its bi-directional interaction with a lively bridge. Through theory and numerics, we demonstrate that pedestrian-bridge interactions can induce bistable lateral gaits such that switching between the gaits can initiate large-amplitude wobbling. We also analyze the role of stride frequency and the pedestrian's mass in hysteretic transitions between the two types of wobbling. Our results support a claim that the overall foot force of pedestrians walking out of phase can cause significant bridge vibrations.

Igor Belykh
Department of Mathematics and Statistics
Georgia State University
ibelykh@gsu.edu

Russell Jeter
Georgia State University
russell.jeter@outlook.com

Vladimir Belykh
Lobachevsky State University of Nizhny Novgorod, Russia
belykh@unn.ac.ru

MS84

A Consensus Dynamics with Delay-Induced Instability can Self-Regulate for Stability via Agent Regrouping

Dynamics of many multi-agent systems is influenced by communication/activation delays D. In the presence of delays, there exists a certain margin called the delay margin DM determining the largest delay with which the system stability holds (D ¡ DM). This margin depends strongly on agents dynamics and the agent network. In this talk, three key elements, namely, the delay margin, network graph, and a distance threshold conditioning two agents connectivity are considered in a multi-agent consensus dynamics under delay D. We report that when the dynamics is unstable under this delay (D ¿ DM), its states can still remain bounded, even for arbitrarily large threshold values, preventing agents to disperse indefinitely. This mechanism can also make the system recover stability in a self-regulating manner, mainly induced by complete network separation and enhanced delay margin. Under certain conditions, unstable consensus dynamics can even keep separating into smaller stable subnetwork dynamics until all agents stabilize in their respective subnetworks.

Rifat Sipahi
Department of Mechanical and Industrial Engineering
Northeastern University
rifat@coe.neu.edu

Min Hyong Koh
Northeastern University
koh.m@husky.neu.edu

MS84

Spotting Leaders in Groups of Self-propelled Particles

In animal groups, collective behavior affords several advantages in avoiding predators, foraging, and mating. Collective motion manifests into highly coordinated maneuvers, determined by local interactions among individuals. Understanding the mechanisms behind these interactions is central to elucidate the hows and whys collective behavior. A particularly critical question is to detect and classify leader-follower relationships in the group. In the technical literature, several methods have been proposed to reconstruct static interaction networks in coupled dynamical systems, including linear correlation analysis, Granger causality, transfer entropy, and event synchronization. While these analyses have been helpful in reconstructing network models from neuroscience to public health, rules on the most appropriate method to use for a specific dataset are lacking. Their application to the study of collective motions is particularly challenging due to the time-varying nature of the underlying interaction networks. In this talk, we demonstrate the possibility of spotting leaders in a group from raw positional data, in an authentic data-driven, model-free approach. Our approach cogently combines estimations from two or more network reconstruction methods to maximize accuracy. We test our framework on synthetic data of groups of self-propelled particles where a single agent acts as a leader and we offer insight on the application of the approach to study fish schooling.

Violet Mwaffo, Maurizio Porfiri
Dept. of Mechanical and Aerospace Engineering
New York University Polytechnic School of Engineering
vmwaffo@nyu.edu, mporfiri@nyu.edu

MS84

Synchronization and Pinning Control of Smooth and Piecewise-smooth Networks with Noise

This talk will be focused on the study of synchronization in networks of nonlinear dynamical systems affected by noise. Specifically, we will provide sufficient conditions for synchronization, which explicitly link together network topology, nodes' dynamics and noise diffusion. We will first consider smooth nodes dynamics and then present some extensions to networks of nodes with piecewise-smooth dynamics. After introducing the key theoretical results, we discuss how the theoretical results can be used to devise synchronization schemes based on pinning (controlling) the dynamics of a fraction of the network nodes. The effectiveness of the methodology will be validates on a set of relevant applications in Smart Cities and Systems Biology.

Giovanni Russo
IBMIreland Research Lab, Dublin, Ireland
grusso@ie.ibm.com

Mario Di Bernardo
University of Bristol
Dept of Engineering Mathematic
m.dibernardo@bristol.ac.uk

MS85

Gevrey Properties for Center Manifolds of Delay Differential Equations

We consider a system of delay equations of the form

$$\begin{aligned}\dot{x}(t) &= \epsilon(t)\\ \dot{y}(t) &= ay(t)+by(t-h)+\epsilon(t)F(x(t),y(t),y(t-h),\epsilon(t))\\ \dot{\epsilon}(t) &= 0,\end{aligned}$$

where F is a holomorphic function of its variables and conditions are imposed on a and b which guarantee that the center manifold of this system is two dimensional. Using techniques similar to the ones used in [M. Canalis-Durand, J.-P. Ramis, R. Schäfke, and Y. Sibuya. Gevrey solutions of singularly perturbed differential equations. *J. Reine Angew. Math.*, 2000.] we show that the center manifold is Gevrey asymptotic to its Taylor series. The Gevrey property can be seen as something in between infinite smoothness and being holomorphic. As such this result improves what is known from general center manifold theory.

Karel Kenens
Hasselt University
Belgium
karel.kenens@uhasselt.be

MS85

Delay Equations for Epidemic Models with Waning Immunity

In this talk we discuss dynamical aspects of delay equations for epidemic models with waning immunity. We introduce a mathematical model formulated by a system of delay differential equations in order to give a possible explanation of periodic outbreak of mycoplasma pneumoniae observed in Japan. Stability analysis and numerical studies for periodic solutions will be presented together with biological interpretations. We also discuss global asymptotic stability of SIS type epidemic model. The talk is based on a collaboration work with G. Kiss, R. Omori, G. Rost and G. Vas.

Yukihiko Nakata
Shimane University
Japan
yunayuna.na@gmail.com

MS85

Constant, Distributed and State Dependent Delays in Models of Waning and Boosting of Immunity

Abstract Not Available At Time Of Publication.

Gergely Rost
Bolyai Institute, University of Szeged
Szeged, Aradi vértank tere 1, H-6720 Hungary
rost@math.u-szeged.hu

MS85

Feedback Stabilizability with Time-Delayed Feedback

Time-delayed feedback control is one of the most successful methods to discover dynamically unstable features of a dynamical system in an experiment. This approach feeds back only terms that depend on the difference between the current output and the output from a fixed time T ago. Thus, any periodic orbit of period T in the feedback-controlled system is also a periodic orbit of the uncontrolled system, independent of any modelling assumptions. It has been an open problem whether this approach can be successful in general, that is, under genericity conditions similar to those in linear control theory (controllability), or if there are fundamental restrictions to time-delayed feedback control. We show that, in principle, there are no restrictions. This paper proves the following: for every periodic orbit satisfying a genericity condition slightly stronger than classical linear controllability, one can find control gains that stabilize this orbit with extended time-delayed feedback control. While the papers techniques are based on linear stability analysis, they exploit the specific properties of linearizations near autonomous periodic orbits in nonlinear systems, and are, thus, mostly relevant for the analysis of nonlinear experiments.

Jan Sieber
University of Exeter
j.sieber@exeter.ac.uk

MS86

Piecewise-Smooth Networks

The aim of this talk will be to discuss the problem of studying convergence in networks of piecewise smooth dynamical systems. This class of networks arises often in those applications where systems affected by discontinuities on a macroscopic timescale are coupled together. Examples include coupled mechanical systems with impacts and friction (such as those in automotive drivelines), networks of power electronic converters, mobile robots etc. I will start by proposing a classification of such networks in terms of the source of their discontinuities and then present our latest results on studying convergence and the emergence of synchronous collective behaviour in these networks. The approach is based on the use of global results from differential stability analysis of dynamical systems and contraction theory. Other approaches will be also discussed and contrasted with Lyapunov based techniques. All theoretical derivations will be illustrated by a set of representative applications.

Mario Di Bernardo
University of Bristol
Dept of Engineering Mathematic
m.dibernardo@bristol.ac.uk

MS86

Functional Asynchronous Networks

We have developed a theory of asynchronous networks that gives a theoretical and conceptual framework for the study of network dynamics where nodes can evolve independently of one another, be constrained, stop, and later restart, and where the interactions between different components of the network may depend on time, state, and stochastic effects – features characteristic of networks in technology, neuroscience and biology. Dynamics is typically piecewise smooth and there are relationships with Filippov systems. In this talk we describe the theory of functional asynchronous networks and give a decomposition theorem that allows one to understand the function of the network in terms of the function of constituent subnetworks. The theorem addresses a question raised by Alon in his book on systems biology: "Ideally, we would like to understand the dynamics of the entire network based on the dynamics of the individual building blocks.' Nonsmoothness is a crucial ingredient needed for the result. In networks modelled by smooth dynamical systems, all nodes are effectively coupled to each other at all times and information propagates instantly across the entire network. A spatiotemporal decomposition is only possible if the network dynamics is nonsmooth and (subsets of) nodes are allowed to evolve independently of each other for periods of time. This allows the identification of dynamical units, each with its own function.

Michael Field
Rice University and Imperial College London
mikefield@gmail.com

Christian Bick
University of Exeter, UK
bick@maths.ox.ac.uk

MS86

Synchronization in On-off Stochastic Networks: Windows of Opportunity

We study dynamical networks whose topology stochastically changes, on a time scale that ranges from fast to slow. Most of the current understanding of synchronization in evolving networks relies on the fast switching hypothesis, where the network dynamics evolves at a much faster time scale than the individual units. In this talk, we go beyond fast switching and reveal unexpected windows of intermediate switching frequencies in which synchronization in the evolving network becomes stable even though it is unstable in the averaged/fast-switching network. We consider networks of both continuous-time [R. Jeter and I. Belykh, "Synchronization in on-off stochastic networks: windows of opportunity", IEEE Transactions on Circuits and Systems I: Regular Papers (2015)] and discrete-time [O. Golovneva, et al., "Windows of opportunity for synchronization in coupled stochastic maps," Physica D (2017)] oscillators. For discrete-time oscillators, we analytically demonstrate the emergence of windows of opportunity and elucidate their nontrivial relationship with the stability of synchronization under static coupling.

Russell Jeter
Georgia State University
russell.jeter@outlook.com

Olga Golovneva
New York University Polytechnic School of Engineering
om628@nyu.edu

Maurizio Porfiri
Dept. of Mechanical and Aerospace Engineering
New York University Polytechnic School of Engineering
mporfiri@nyu.edu

Igor Belykh
Department of Mathematics and Statistics
Georgia State University
ibelykh@gsu.edu

MS86

Community Change-point Detection in Time-dependent Networks

Time-dependent networks are frequently used to represent complex systems in which dynamic interactions occur over time. Understanding if, when and how such networks change over time can provide valuable insights into how complex systems evolve. However, the variation in individual pairwise interactions can be hard to interpret and is often not particularly meaningful on its own. Instead, community detection can be used to identify a more readily interpretable, coarse-grained representation of the system. Here we use a hierarchical model to capture stochastically equivalent nodes across multiple resolutions and introduce an efficient spectral method for inferring the community assignment. We then apply methods from statistical change-point detection to detect significant changes in the large-scale structure of the network.

Michael Schaub
Massachusetts Institute of Technology
mschaub@mit.edu

Leto Peel
Universite catholique de Louvain
leto.peel@uclouvain.be

MS87

Modelling Movement and Coordination in the Mirror Game: From Dyads to Groups

This talk will start with a brief overview of the problem of modelling the emergence of synchronization and coordination between humans performing a joint task. Attention will be focussed on the mirror game, a paradigmatic example where two players need to coordinate each others motion. The use of dynamical systems models will be presented together with the design of virtual players able to interact with a human player. Then, the problem of modelling the emergence of leadership and coordination in a human ensemble will be described. We will show that the coordination level of the group depends on the specific way in which each individual moves when isolated from the others, and on the pattern of their visual couplings. A mathematical model based on networks of nonlinear oscillators will be proposed to capture and explain the observed group dynamics.

Francesco Alderisio
University of Bristol
Department of Engineering Mathematics
f.alderisio@bristol.ac.uk

Gianfranco Fiore
University of Bristol
gianfranco.fiore@bristol.ac.uk

Robin Salesse, Benoit Bardy
University of Montpellier
salesse.robin@gmail.com, benoit.bardy@umontpellier.fr

Mario Di Bernardo
University of Bristol
Dept of Engineering Mathematic
m.dibernardo@bristol.ac.uk

MS87

Embedded Dynamics of Multiagent Activity and Social Coordination

Multiagent coordination is a common part of everyday social activity. Identifying the dynamic processes that shape and constrain the complex, time-evolving patterns of such coordination often requires the development of dynamical models to test hypotheses and motivate future research questions. Here I review a task dynamic framework for modeling multiagent behavior and social coordination, and illustrate the application of this framework using a range of shepherding and object movement tasks. Emphasizing self-organization, I will highlight how the behavioral coordination that characterizes many multiagent and social activities emerges naturally from the physical, informational, and biomechanical constraints of an agent-environment task context. Using examples from human-robot interaction and artificial agent research, I will also illustrate how task dynamic models that effectively capture the emergent and self-organized nature of human social coordination can be used to develop robust human-machine systems. Such systems have applications in industrial, therapeutic, and assistive technologies contexts where close natural interaction with humans is required.

Maurice Lamb, Patrick Nalepka, Rachel W. Kallen,
Michael J. Richardson
Center for Cognition, Action and Perception
Department of Psychology, University of Cincinnati
maurice.lamb@uc.edu, nalepkpk@mail.uc.edu,
rachel.kallen@uc.edu, michael.richardson@uc.edu

MS87

Using Evolutionary Dynamics to Model Structured Improvisational Dance

We investigate the mechanisms of social decision-making for a structured improvisational dance in which a group of dancers makes a sequence of compositional choices among pre-defined dance motion primitives. We use the replicator-mutator dynamics to model the evolution of fractions of the population of dancers committed to different strategies (dance motion primitives) as a function of replication (commitment to strategies with high fitness) and mutation (spontaneous switching among strategies). Experimental data suggest that dancers make decisions governed by an explore-exploit tradeoff in which the group oscillates between exploiting multiple coexisting primitives and exploring a single new primitive. We adapt the replicator-mutator dynamics to model the dancers movement decisions by introducing a nonlinear fitness function and a feedback controlled bifurcation wherein the mutation rate is driven in a slow time-scale by the population fractions in the fast time-scale. We show how the adapted replicator-mutator dynamics emulate the oscillatory behavior of the dance population in the case of two interacting strategies and can be used to study the phasing of exploration and exploitation in the improvisational dance.

Kayhan Ozcimder, Biswadip Dey
Princeton University
Department of Mechanical and Aerospace Engineering
ozcimder@princeton.edu, biswadip@princeton.edu

Alessio Franci
Universidad Nacional Autónoma de México
México
afranci@ciencias.unam.mx

Rebecca J. Lazier
Princeton University
Program in Dance
rlazier@princeton.edu

Daniel Trueman
Princeton University
Department of Music
dtrueman@princeton.edu

Naomi E. Leonard
Princeton University
Department of Mechanical and Aerospace Engineering
naomi@princeton.edu

MS87

Behavioral Dynamics of Collective Crowd Behavior

The collective behavior of flocks, schools, and human crowds is thought to emerge from local interactions between individuals. There are many models of such collective motion, but very little experimental evidence. The behavioral dynamics approach [Warren W.H. 2006 The dynamics of perception and action. Psychological Review 113, 358-389] seeks to explain these global patterns by characterizing the dynamics of the local interactions, and using them to predict the emergent collective motion. Taking a local-to-global approach, we have developed a pedestrian model that captures elementary behaviors such as steering, obstacle avoidance, and pedestrian interactions, based on experiments in virtual reality [Warren W.H., Fajen B.R. 2008 Behavioral dynamics of visually-guided locomotion. In Coordination: Neural, behavioral, and social dynamics (A. Fuchs, V. Jirsa, Eds.), Heidelberg, Springer]. I will focus on recent work that characterizes the visual coupling between a pedestrian and multiple neighbors in a virtual crowd, yielding a novel neighborhood structure. Reciprocally, taking a global-to-local approach, we collect motion-capture data on human crowds in key scenarios. Patterns of collective motion are analyzed and can be reproduced using agent-based simulations with just a few elementary behaviors. The results support the view that crowd behavior emerges from pedestrian interactions, without internal models or plans, consistent with principles of self-organization.

William Warren
Brown University
Cognitive, Linguistic and Psychological Sciences
bill_warren@brown.edu

MS88

Predicting the Shapes of Eco-Evolutionary Predator-Prey Cycles Using Fast-Slow Dynamical System Theory: Fast Evolution and Slow Ecology, Vice Versa, and Everything in Between

Evolution in predator species, prey species, or both species can alter the shapes of predator-prey cycles. In particular, in the absence of evolution, predator oscillations are predicted to lag behind prey oscillations by a quarter period. In contrast, evolution in one species can increase the lag to a half-period and coevolution can reverse the cycles and cause predator peaks to occur before prey peaks. In this talk, I explore how the occurrence of cycles and the observed phase lags depend on the relative time scales of the ecological and evolutionary processes. In particular, using fast-slow dynamical systems theory, I identify what kinds of cycles occur in the limit where the ecological dynamics are much faster than the evolutionary dynamics and in the opposite limit where the ecological dynamics are much slower than the evolutionary dynamics. I then use bifurcation theory to identify when cycles are lost/born and how cycle shape is altered as the relative times scales of the ecological and evolutionary variables are changed. This work shows how the stabilities of the ecological and evolutionary subsystems can be used to predict when cycles will be born or lost and cycle shape.

Michael Cortez
Utah State University
michael.cortez@usu.edu

MS88

Rapid Evolution in Plankton Populations: A Slow-Fast Model

Abstract Not Available At Time Of Publication.

Frits Veerman
University of Edinburgh
f.veerman@ed.ac.uk

MS88

Applications of Timescale Analysis to Mathematical Models in Toxicology

The modelling of many biological systems typically involves some form of abstraction via proposed sets of reaction pathways of interacting elements, leading naturally to systems of differential equations. It is very common using biologically relevant parameters that the predicted solutions form clear distinct phases of events as a consequence of there being a large/small parameter. Singular perturbation analysis is a powerful tool to systematically identify and draw out relevant simplified models for each of these distinct phases, enabling the identification of the important and unimportant biological processes involved. Moreover, parameter combinations at which qualitative shifts in solutions often present themselves naturally from the analysis. In principle the analysis can be applied to a system of differential equations of any size, and the main focus of the talk will be on a relatively large system (10 ODEs) describing the toxicological action of a drug called nitisinone, whereby despite its complexity a full description of the evolution of all components can be determined, including a number of aspects of pharmacological interest. Further examples from microbiology and epidemiology will briefly be presented to demonstrate the broad utility of the analytical approach.

John P. Ward
Loughborough University, UK
john.ward@lboro.ac.uk

MS89

Quantum Control and the Geometry of Flag Manifolds

In this talk we discuss aspects of the physics and mathematics of a quantum control system interacting with its environment. In particular we discuss the control of an finite-dimensional dissipative Lindblad system by considering the geometry of its orbit and interorbit dynamics. This entails considering the geometry of the system, the structure of the Lindblad operator, and the convexity associated with the density equation. Applications are given to constructing pure states. We will also discuss the general structure of controlled quantum and nonlinear systems. This includes recent work with Rooney and Rangan.

Anthony M. Bloch
University of Michigan
Department of Mathematics
abloch@umich.edu

MS89

The Siegel Upper Half Space, Symplectic Reduction, and Gaussian Wave Packet Dynamics

I will talk about the symplectic geometry behind the dynamics of the Gaussian wave packet, particularly the role of the Siegel upper half space in parametrizing the Gaussian wave packet. The Siegel upper half space is the set of symmetric complex matrices with positive-definite imaginary parts. Understanding the geometry of this space gives insights into the description of the dynamics of the Gaussian wave packet. Particularly, I will show that the Siegel upper half space is an example of the Marsden–Weinstein quotient of symplectic reduction. The result provides a connection between two different formulations of Gaussian wave packet dynamics as Hamiltonian dynamical systems via symplectic reduction.

Tomoki Ohsawa
The University of Texas at Dallas
Department of Mathematical Sciences
tomoki@utdallas.edu

MS89

Lagrange-Dirac Systems for Nonequilibrium Systems

Abstract Not Available At Time Of Publication.

Hiroaki Yoshimura
Waseday University

yoshimura@waseda.jp

MS89

Hamel's Formalism for Constrained Field Theories

Separation of the position and velocity measurements in mechanics originated in Euler's work on the dynamics of rigid body and fluid. Hamel extended this formalism from the rigid body setting to arbitrary finite-dimensional Lagrangian mechanical systems. This talk will introduce Hamel's formalism for classical field theories, with an emphasis on the dynamics of constrained continuum-mechanical systems.

Dmitry Zenkov
North Carolina State University
Department of Mathematics
dvzenkov@ncsu.edu

MS90

Self-Organization and Pattern Formation in Auxin Flux

The plant hormone auxin plays a central role in growth and morphogenesis. In the shoot apical meristem the auxin flux is polarized through its interplay with PIN proteins. Concentration based mathematical models of the auxin flux permit to explain some aspects of phyllotaxis, where auxin accumulation points act as auxin sinks and correspond to primordia. Simulations show that these models can reproduce geometrically regular patterns like spirals in sunflowers or Fibonacci numbers. We propose a mathematical study of a related non-linear o.d.e. using Markov chain theory. We will next consider a concurrent model which is based on the so-called flux hypothesis, and show that it can explain the self-organization of plant vascular systems.

Christian Mazza
University of Fribourg
Switzerland
christian.mazza@unifr.ch

MS90

Fibonacci Phyllotaxis: Models, Data and Alan Turing

Turing worked on his morphogenetic theory over the last years of his life (Dawes, 2016). He claimed to be able to explain the phenomenon of Fibonacci phyllotaxis: he studied the properties of lattices arising from repeated placements of mutually repelling organs, and aimed to show that as the patterns deform the stable branch of the resulting bifurcation pattern maintains Fibonacci structure (Swinton, 2013). Only after his death was the generic nature of Fibonacci phyllotaxis demonstrated in exactly this mathematical sense. The molecular biology of phyllotaxis has been increasingly well characterised, with little input from this mathematics. But sunflowers really do commonly have 89 spirals, and this fact will not be explicable on a molecular basis without such input. One key approach will be to examine how plant developmental structure responds to perturbation and defect. Sunflower heads which are not perfect specimens with clear Fibonacci structure are the most informative for this. Thanks to a citizen science experiment run by the Museum of Science and Industry, Manchester we can see some of the challenges these models face (Swinton, 2016). Fibonacci structure in plants should provide a fertile ground for a new generation of mathematical biology.

Jonathan Swinton
Deodands Ltd
jonathan@swintons.net

MS90

Beyond Wave-Pinning; Dynamical Mechanisms for Cell Polarity and Interdigitation

The asymmetrical profile presented by the concentration of proteins in Eukaryotic cells is the signature of cell polarisation, a key process in developmental biology. Reaction diffusion models have been proposed in order to describe this breaking of symmetry. They rely on two qualitatively different mechanisms: mass-conservation (wave-pinning models) and diffusion driven instablility (Turing models). In this talk we investigate the connection between both mechaisms by studying a generalised version of the wave-pinning model, when generic source and loss terms are added. The new terms give rise to several non-homogeneous spatial equilibrium solutions, namely, peaks, patterns and localised patterns. We fininish the analysis by studying the limit when both non-conservative terms vanish, we find a continuous connection between the peak spatial solution and the fronts observed in the wave pinning model. The last part of this talk is devoted to the study of the intriguing interdigitation pattern observed in the interface between two adjacent pavement cells on the surface of leaves in plants.

Nicolas Verschueren Van Rees, Alan R. Champneys
University of Bristol
nv13699@bristol.ac.uk, a.r.champneys@bristol.ac.uk

MS91

Topological Analysis of Mapper and Multiscale Mapper

Summarizing topological information from datasets and maps defined on them is a central theme in topological data analysis. Mapper, a tool for such summarization, takes as input both a possibly high dimensional dataset and a map defined on the data, and produces a summary of the data by using a cover of the codomain of the map. This cover, via a pullback operation to the domain, produces a simplicial complex connecting the data points. Inspired by the concept, we explored a notion of a tower of covers which induces a tower of simplicial complexes connected by simplicial maps, which we call multiscale mapper. We study the resulting structure, its stability, and design practical algorithms to compute its persistence diagrams efficiently. In a recent work we discovered further connections between the mapper, its multiscale version and the domain of the map that defines them. Specifically, we can now answer the question "what does a mulitscale mapper reveal?' more affirmatively.

Tamal Dey
The Ohio State University
tamaldey@cse.ohio-state.edu

MS91

The Conley Index for Sampled Dynamical Systems

In late 90' R. Forman [R.Forman, Morse Theory for Cell Complexes, *Advances in Mathematics* (1998)] introduced the concept of a combinatorial vector field on a CW complex and presented a version of Morse theory for such fields. Recently the theory has been extended towards topological dynamics on CW complexes, in particular the Conley index theory [M. Mrozek, Conley-Morse-Forman theory for combinatorial multivector fields on Lefschetz complexes, *Foundations of Computational Mathematics*, (2016)]. The extension is motivated by the study of dynamics known only from a sample as in the case of time series dynamics. It covers such concepts as attractors, repellers, Morse decompositions, Conley-Morse graphs, stability and continuation. We will discuss the foundations of the theory, the bridges between the classical and combinatorial theory [T. Kaczynski, M. Mrozek, and Th. Wanner, Towards a Formal Tie Between Combinatorial and Classical Vector Field Dynamics, *Journal of Computational Dynamics*,(2016)] and some algorithmic aspects of the theory [T. Dey, M. Juda, T. Kapela, M. Mrozek, and M. Przybylski, Research in progress].

Marian Mrozek
Jagiellonian University, Krakow, Poland
mrozek@ii.uj.edu.pl

MS91

Applications of Persistence to Time Series Analysis

A time series is simply a stream of data. However, the type of output of this stream can be many different things. The most commonly studied and most understood form of time series is real-valued, however this is certainly not the only way that time series are presented in practice. For instance, a movie can be interpreted as a matrix-valued time series. In this talk, we will look at two applications in different domains. Both of these applications utilize persistent homology to provide analysis even though the types of time series under study are quite different. First, we will discuss the phenomenon of chatter in machining dynamics. Chatter is the undesirable behavior exhibited by a cutting tool which is characterized by large amplitude vibrations that result in non-smooth metal parts, as well as an intense noise. Combining Taken's embedding theorem, persistence, and machine learning methods gives 97% accuracy when attempting to predict and prevent this behavior. Second, we will use persistence to quantify a diurnal cycle recently observed in IR hurricane data. In this case, we turn a matrix valued time series into a persistence diagram valued time series and investigate the resulting periodic behavior in persistence diagram space.

Elizabeth Munch
University at Albany
emunch@albany.edu

MS91

The Topological Shape of Brexit and Time-Dependent Functional Networks

Persistent homology is a method from computational algebraic topology that can be used to study the "shape" of data. We consider two examples. In a slightly snarky (but illustrative) introductory example, we use the weight rank clique filtration and the VietorisRips filtration on a pair of data sets that are related to the 2016 European Union "Brexit" referendum in the United Kingdom. We then switch gears and use PH to study "functional networks" that we construct from time-series data from both experimental sources (neuroimaging) and synthetic sources (coupled Kuramoto oscillators). One of our insights is that the position of the features in a filtration can sometimes play a more vital role than persistence in the interpretation of topological features, even though conventionally the latter is used to distinguish between signal and noise.

Mason A. Porter
University of Oxford
Mathematical Institute
mason@math.ucla.edu

Heather Harrington
Mathematical Institute
University of Oxford
harrington@maths.ox.ac.uk

Bernadette Stolz
University of Oxford
bernadette.stolz@lincoln.ox.ac.uk

MS92

Dmd-Galerkin Approximation for Nonlinear Dynamical Systems

Dynamic Mode Decomposition (DMD) is a recently developed technique for obtaining reduced order models for nonlinear dynamical systems. In this talk, we will compare the use of DMD as equation free modeling and Galerkin projection method through numerical examples.

Alessandro Alla
Department of Scientific Computing
Florida State University, USA
aalla@fsu.edu

MS92

Fast and Reliable Extraction of Coherent Features from Models and Data using the Dynamic Laplace Operator

Transport and mixing properties of aperiodic flows are crucial to a dynamical analysis of the flow, and often have to be carried out with limited information. Finite-time coherent sets are regions of the flow that minimally mix with the remainder of the flow domain over the finite period of time considered; they thus provide a skeleton of distinct regions around which more turbulent flow occurs. Finite-time coherent sets manifest in geophysical systems in the forms of e.g. ocean eddies, ocean gyres, and atmospheric vortices. In real-world settings, often observational data is scattered and sparse, which makes the already difficult problem of coherent set identification and tracking even more challenging. We develop FEM-based numerical methods that rapidly and reliably extract finite-time coherent sets from models or scattered, possibly sparse, trajectory data. The numerical methods are based on a dynamic Laplace operator, whose eigenfunctions identify regions in phase space with persistently small boundary size relative to enclosed volume. Oliver Junge will discuss related work in the MS "Set oriented and transfer operator methods for turbulent flows".

Gary Froyland
UNSW Australia
g.froyland@unsw.edu.au

MS92

Extraction and Prediction of Coherent Patterns in

Fluid Flows Via Space-Time Koopman Analysis

We discuss a method for detecting and predicting the evolution of coherent spatiotemporal patterns in incompressible fluid flows. The approach is based on a representation of the Koopman operator governing the evolution of observables in a smooth basis learned from velocity field data through the diffusion maps algorithm. This representation enables the detection of coherent flow patterns through Koopman eigenfunctions and simulation of the evolution of observables and probability densities under the flow map. We present applications in Gaussian vortex flows and chaotic flows generated by Lorenz 96 systems.

Dimitrios Giannakis
Courant Institute of Mathematical Sciences
New York University
dimitris@cims.nyu.edu

MS92

Optimally Time Dependent Modes for the Description of Finite-Time Instabilities in Infinite Dimensional Dynamical Systems

High-dimensional chaotic dynamical systems can exhibit strongly transient features. These are often associated with instabilities that have finite-time duration. Because of this finite-time character of these transient events it is hard to detect the associated subspaces where these 'live' based on long term averages or information about the statistical steady-state. Here we utilize a recently developed framework, the optimally time-dependent (OTD) modes, to extract a time-dependent subspace that spans the modes associated with transient features associated with finite-time instabilities. This time-dependent subspace encodes the temporal correlation of these transient events. Most importantly, the effectiveness of the method does not depend on the physical dimensionality of the system or the intrinsic dimensionality of the underlying attractor. Specifically, we show that the OTD modes, under appropriate conditions, converge exponentially fast to the eigendirections of the Cauchy-Green tensor associated with the most intense finite-time instabilities. The case where eigenvalue crossing occurs may lead to instantaneous interruption of this convergence and such cases are thoroughly presented and analyzed through specific examples. We apply our analysis for the parsimonious computation of Finite-Time Lyapunov Exponents for high dimensional systems and demonstrate numerically the validity of the theoretical findings.

Themistoklis Sapsis
Massachusetts Institute of Techonology
sapsis@mit.edu

MS93

Dynamics and Resilience of Vegetation Bands in the Horn of Africa: Comparing Observation and Modeling

Bands of vegetation alternating with bare soil in rhythmic succession have been well known in the Horn of Africa and elsewhere since the 1950s. Modeling efforts over the past two decades have sought to account for the emergence of these patterns via a self-organizing interaction between vegetation and water resources. A number of predictions have been made using such models, but many important predictions pertaining to vegetation resilience under environmental and human pressure have been underconstrained by a lack of long-term observation. High-resolution aerial survey photographs taken over the Horn of Africa in the 1940s and 50s represent one of the earliest and richest records of vegetation banding. We combine such photographs from the early 1950s with present-day satellite imagery, identifying the locations of the old images, and comparing the status of the vegetation. For many areas, changes in the vegetation patterns are surprisingly modest, with individual bands remaining identifiable with their precursors in the early images. However, others areas have developed substantially since the 1950s, with bands nearly disappearing from the sites. Many bands in human-impacted areas exhibit increased upslope colonization alongside diminished productivity, in apparent contradiction with intuition and current theory. In light of this, we suggest a reevaluation of modeling frameworks to take fuller account of human pressures on self-organized vegetation.

Karna V. Gowda
Northwestern University
karna.gowda@u.northwestern.edu

Sarah Iams
Harvard University
Cambridge, MA
siams@seas.harvard.edu

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

MS93

Predictability of Critical Transitions

Critical transitions in multi-stable systems have been discussed as models for a variety of phenomena ranging from the extinctions of species to socio-economic changes and climate transitions between ice-ages and warm-ages. From bifurcation theory we can expect certain critical transitions to be preceded by a decreased recovery from external perturbations. The consequences of this critical slowing down have been observed as an increase in variance and autocorrelation prior to the transition. However especially in the presence of noise it is not clear, whether these changes in observation variables are statistically relevant such that they could be used as indicators for critical transitions. In this contribution we investigate the predictability of critical transitions in conceptual models. We study several fast slow-systems under the influence of external noise. We focus especially on the statistical analysis of the success of predictions and the overall predictability of the system. The performance of different indicator variables turns out to be dependent on the specific model under study and the conditions of accessing it. Furthermore, we study the influence of the magnitude of transitions on the predictive performance.

Sarah Hallerberg
Network Dynamics, Max Planck Inst. Dynamics and Self-Org.
shallerberg@nld.ds.mpg.de

Christian Kuehn
Technical University of Munich
ckuehn@ma.tum.de

Nahal Sharafi, Xiaozu Xhang
Max Planck Institute

nahal@nld.ds.mpg.de, xzhang@nld.ds.mpg.de

MS93

Partial Eclipse of the Heart: Early Warning Signs from Sparse Observations

The Pediatric Early Warning Score (PEWS) was designed to ensure that pediatric hospital patients receive assistance before their conditions constitute an emergency. PEWS has significantly decreased the rate of pediatric cardiac arrest outside of the ICU and subsequently the pediatric mortality rate. However, approximately 15% of deteriorating patents are missed entirely by PEWS, and in some studies the median lead time is only 30 minutesinsufficient time to prep an ICU and implement a preventive response. Efforts have shifted to finding robust methods of determining at-risk patients earlier in the process. Cerner Math has developed an improved early warning system called PEWS*. Where PEWS only uses the most current observation, PEWS* utilizes past observations. By utilizing a multivariate time series rather than static observations, we are able to provide 2-6 hours additional warning.

Andrew Roberts
Department of Mathematics
Cornell University
andrew.roberts@cornell.edu

MS93

Bifurcations in the Dynamic Budyko Model with Diffusive Heat Transport

We consider Budyko's energy balance climate model, with diffusive meridional heat transport, coupled with a dynamic ice line equation. We present bifurcations in the coupled model with parameters aligned with the modern climate. Adjusting the governing equations to model the extensive glacial episodes of the Neoproterozoic Era, we show there exists a stable equilibrium with the ice line in tropical latitudes. We also present several bifurcation scenarios appearing in this latter model.

James Walsh
Oberlin College
jawalsh@oberlin.edu

MS94

Coherency in Braids of Trajectories As a Machine-Learning Problem

A sparse set of Lagrangian trajectories can be used to construct a topological braid to represent the planar incompressible flow that generated the trajectories. In the braid setting, only topological information about trajectories is retained, and their precise spatial coordinates ignored. We approach the problem of defining and identifying coherent structures with the braid representation as the starting point. After a review of previous results, we formulate the machine learning problem of identifying which trajectories can be grouped into coherent bundles, based on the effect their motion has on stretching of topological material curves (loops). We propose one approach for solving this machine learning problem and demonstrate its results on a fluid flow that contains both chaotic and regular trajectories.

Marko Budisic
Department of Mathematics
Clarkson University
marko@clarkson.edu

Jean-Luc Thiffeault
Dept. of Mathematics
University of Wisconsin - Madison
jeanluc@math.wisc.edu

MS94

Weakly Three-Dimensional Transport by Vortices in SQG Flows

The surface quasi-geostrophic (SQG) equations are a model for low-Rossby number geophysical flows in which the dynamics are governed by potential temperature dynamics on the boundary. The model can be used to explore the transition from two-dimensional to three-dimensional mesoscale geophysical flows. In the approximation of linear stratification and f-plane, we examine the dynamics of SQG vortices and the resulting three-dimensional flow including at first order in Rossby number ($O(Ro)$). This requires solving an extension to the usual QG equation to compute the velocity corrections. It is straightforward to obtain the vertical velocity, but difficult to find the $O(Ro)$ horizontal corrections. The newly-developed Finite Time Braiding Entropy (FTBE) from Thiffeault & Budisic is used to quantify the chaotic mixing induced by three point vortices. We also consider the exact SQG vortex solution developed by Dritschel (2011) from the limit of a QG ellipsoid of constant potential vorticity and its transport properties.

Stefan Llewellyn Smith
Department of MAE
University of California, San Diego
sgls@ucsd.edu

Cecily Taylor
UCSD
cecilyktaylor@gmail.com

MS94

Trajectory Encounter Number As a Diagnostic of Mixing Potential in Fluid Flows

Fluid parcels can exchange water properties when coming in contact with each other, leading to mixing. The trajectory encounter number, which quantifies the number of fluid parcel trajectories that pass close to a reference trajectory over a finite time interval, is introduced as a measure of the mixing potential of a flow. Regions characterized by low encounter numbers, such as cores of coherent eddies, have low mixing potential, whereas turbulent or chaotic regions characterized by large encounter numbers have high mixing potential. The encounter number diagnostic was used to characterize mixing potential in 3 flows of increasing complexity: the Duffing Oscillator, the Bickley Jet, and the altimetry-based velocity in the Gulf Stream Extension region. An additional example was presented where the encounter number was combined with the u-star-approach of Pratt et al., 2016 to characterize the mixing potential for a specific tracer distribution in the Bickley Jet flow. Analytical relationships were derived connecting encounter number to diffusivity for purely-diffusive flows, and to shear and strain rates for linear shear and linear strain flows, respectively. It is shown that in a diffusive regime the encounter number grows as a square-root of time, whereas in a linear shear and strain flows the encounter number is proportional to time.

Irina Rypina

Woods Hole Oceanographic Institution
irypina@whoi.edu

Larry Pratt
Woods Hole Oceanographic Inst.
lpratt@whoi.edu

MS94

Winding Angle Distribution of 2D Brownian Motion with Vortical Flow

Let the winding angle distribution with respect to the origin of the standard 2D Brownian motion be $\theta(t)$. As proved by Spitzer, $2\theta(t)/\ln(t)$ converges in distribution to standard Cauchy, for infinitely large t. We show that, in the presence of an additional tangential flow induced by a vortex at the origin, $N_1(t)/\theta(t)$ converges to Gamma(1/2,1/2), where $N_1(t)$ is some normalizer. In particular, $\theta(t)/N_1(t)$ is always in the direction of the flow and has heavy tail just as in Spitzer's original case, due to the large winding near the origin. To regularize the heavy tail, we also study winding outside an obstacle and inside an annulus. In the former case, $\theta(t)/N_2(t)$is given in terms of an elliptic theta function, while in the latter case, $(\theta(t) - At)/B\sqrt{t}$ is standard Gaussian, where $N_2(t)$ is some normalizer and A, B are some constants.

Huanyu Wen
University of Wisconsin - Madison
Department of Mathematics
wen@math.wisc.edu

MS95

Extreme Value Analysis in Dynamical Systems: Two Case Studies

Extreme Value Theory for deterministic dynamical systems is a rapidly developing area of research. This contribution presents numerical analyses designed to show particular features of extreme value statistics (EVS) in dynamical systems, and also to explore the validity of the theory. We find that formulae that link the EVS with geometrical properties of the attractor hold typically for high-dimensional systems whether a so-called geometric distance observable or a physical observable is concerned. In very low-dimensional settings, however, the fractality of the attractor prevents the system from having an extreme value law (EVL), which might well render the evaluation of EVS meaningless and so ill-suited for application. Only for distance observables can we recover an EVL exactly, even in a low-dimensional setting, when lumped block maxima data are considered measuring the distance from various points all over the attractor. The latter corresponds to an averaging and thereby smoothing of unsmooth extreme value distributions.

Tamas Bodai
Meteorological Institute
University of Hamburg
tamas.bodai@uni-hamburg.de

MS95

Tipping Due to Extreme Events

Extreme events can be considered as very rare events having a large impact on a physical or natural system. Such events can be either recurrent or can happen as a single large perturbation. In case of recurrent events they might be characterized as noise with a certain non-Gaussian probability distribution. In general, those probability distributions have fat tails accounting for the enhanced probability of extreme events. An even more extreme noise can be realized as an on-off intermittency, which consists of many small perturbations interspersed with large events. We study tipping behavior in bistable systems subject to such perturbations. We show that intermittent noise leads qualitatively to similar stability properties as known for Gaussian noise (N-tipping) expressed as the Arrhenius law for the mean escape time. However, quantitatively the same attractor appears to be more stable with respect to intermittent noise than for Gaussian noise. We compare our results to the case of a single perturbation, which can be considered as E-tipping (event-tipping). To this end we compute the minimal perturbation necessary to leave the attractor, i.e. the minimal distance between attractor and the boundary of its basin of attraction. The algorithm used to compute this minimal perturbation is based on an optimization procedure introduced to estimate the minimal seed leading from a laminar to a turbulent state in fluid mechanics.

Ulrike Feudel
University of Oldenburg
ICBM, Theoretical Physics/Complex Systems
ulrike.feudel@uni-oldenburg.de

Lukas Halekotte
University of Oldenburg ICBM,
Theoretical Physics/Complex Systems
lukas.halekotte@uni-oldenburg.de

James A. Yorke
University of Maryland
Departments of Math and Physics and IPST
yorke@umd.edu

MS95

Predicting Extreme Optical Pulses in Laser Systems

In this presentation I will discuss the predictability of ultra-high pulses emitted by optically perturbed semiconductor lasers. Time-delayed optical feedback and continuous-wave optical injection configurations will be considered, both of which produce a chaotic laser output with occasionally rare ultra-high pulses [J. A. Reinoso et al, "Extreme intensity pulses in a semiconductor laser with a short external cavity, Phys. Rev. E 87, 062913 (2013) and C. Bonatto et al, "Deterministic optical rogue waves", PRL 107, 053901 (2011)]. I will consider experimental and simulated data in order to show that nonlinear tools of time-series analysis can allow for a certain degree of predictability of the likelihood of occurrence of extreme intensity fluctuations. In the time series of the laser intensity, symbolic patterns can be identified, which are more likely or less likely to occur before the high intensity pulses. The more likely patterns can be used as "early warning" of an upcoming extreme fluctuation, while the less likely patterns can be used as an indicator of an upcoming "safe time window" where extreme fluctuations are unlikely to occur. This symbolic approach could provide useful information about the predictability of extreme fluctuations in the output signals of many real-world complex systems.

Cristina Masoller
Universitat Politècnica de Catalunya (UPC
Departament de Física i Enginyeria Nuclear (DFEN)

cristina.masoller@gmail.com

MS95

Extreme Events in Coupled Systems with Different Delays

Extreme events are rare, recurrent and aperiodic phenomena which have a large impact on the system. While previous research has identified stochasticity, progressive spatial synchronization, and inhomogeneity of the system to be factors which may cause such events; the impact of time delays — an important factor which often shapes the dynamics of such systems — has not been analyzed for its role in extreme event generation. We investigate a deterministic system of identical FitzHugh-Nagumo oscillators coupled by multiple delay coupling and study the role that such a coupling plays on extreme event generation. The investigations reveal that delay coupling might indeed cause extreme events in such relaxation oscillators even in the absence of all previously reported causal factors. We also note that the generation of extreme events in our system is a manifestation of the intermittency, which is induced in a system when a period doubling cascade leading to chaos collides with a period-adding cascade in an interior crisis. The study also underlines the role of an invariant synchronization manifold and its transverse stability in shaping the mechanism generating the extreme event. The intricate dynamics occurring on this manifold leads to long transients before the system converges to a fixed point or the chaotic attractor. This interplay also results in the formation of riddled basins of attraction with tongue-like structures embedded in them.

Arindam Saha
IISER Kolkata, India
arindamsaha1507@gmail.com

Ulrike Feudel
University of Oldenburg
ICBM, Theoretical Physics/Complex Systems
ulrike.feudel@uni-oldenburg.de

MS96

The Phase Structure of Grain Boundaries

I will present numerical and analytical results on grain boundaries in the Swift-Hohenberg and Cross-Newell equations. It is well known that as the angle made by the roll patterns on each side of this line defect is decreased, dislocations appear at the core of the grain boundary. Understanding this transition is an interesting problem since it provides an example of defect formation in a system that is variational and therefore more amenable to analysis. I will show numerical results of the Swift-Hohenberg equation that aim to analyze the phase structure of far-from-threshold grain boundaries and connect these observations to properties of the associated phase diffusion equation, the regularized Cross-Newell equation. This work is part of a long-term project whose goal is to understand the role played by phase derivatives in the creation of defects in pattern forming systems, and is joint with Nick Ercolani and Nikola Kamburov.

Joceline Lega
University of Arizona, USA
lega@math.arizona.edu

MS96

Spatiotemporal Dynamics in the Space of Persistence Diagrams

The celebrated theorem of Takens, which lays the mathematical foundation for the process of dynamic attractor reconstruction from a time series by the method of delays, has since been generalized and extended by various authors. In particular, Robinson proved a partial extension of delay reconstruction to the setting of infinite-dimensional dynamical systems possessing finite-dimensional attractors by showing that a prevalent set of real-valued 'observation functions' can be used to create an injective map from the attractor in Hilbert space to delay-coordinate space. More recently, tools from computational topology have been used in a host of data-driven applications to summarize topological characteristics of scalar fields into compact representations called persistence diagrams. If these fields are evolving in time—for instance, under a dissipative PDE—a persistence transformation induces continuous dynamics in the space of persistence diagrams, and so may be regarded as a diagram-valued observation function. In this talk, we discuss a first numerical investigation of these induced dynamics with a focus on dynamic and structural properties of the underlying attractors.

Francis Motta
Duke University
Department of Mathematics
francis.c.motta@gmail.com

MS96

How to Wake the Homoclinic Snake on the Surface of a Ferrofluid

In 2017 it is 50 years ago when Cowley & Rosensweig reported on the instability of a horizontal layer of ferrofluid subjected to a vertical magnetic field. The flat layer becomes unstable due to a subcritical bifurcation and a regular hexagonal pattern of spikes emerges. The field regained considerable interest, when localized states of solitary spikes were observed in the hysteretic regime of the magnetic field, where hexagons coexist with the flat layer. The localized states can be generated by pulses of a local magnetic field (Richter *et al.* PRL 2015). Likewise, they arise after a specific pulse sequence of the global field (Gollwitzer *et al.* NJP 2010), which allows to access the vicinity of the unstable branch of the bifurcation. In this way, a sequence of localized patches of hexagons was generated in experiment, indicating for homoclinic snaking, which was corroborated in numerics (Lloyd *et al.* JFM 2015). So far, the experiment gives evidence for slanted snaking, characteristic for a conserved quantity (Firth *et al.* PRL 2007), like the volume of ferrofluid in the vessel. It remains to be investigated how larger vessels or a horizontal field component may modify the snaking in experiments.

Reinhard Richter
University of Bayreuth
reinhard.richter@uni-bayreuth.de

MS96

Time-Dependent Spatiotemporal Chaos in Pattern-Forming Systems with Two Length

Scales

Nonlinear resonant three-wave interactions between two waves with the same wavelength and a third wave with a different wavelength can lead to steady patterns (stripes or rectangles), to simple time-dependent patterns (travelling waves) or to chaotic dynamics, depending on the details of how the three waves transfer energy between the two wavelengths. In a large domain, waves with the two wavelengths and any orientation allowed by the domain can interact in much more complex ways, potentially leading to steady superlattice patterns or quasipatterns, or to time-dependent spatiotemporal chaos. We investigate the conditions that encourage spatiotemporal chaos, and illustrate what can happen in the particular case of a two-layer reaction–diffusion system.

Alastair M. Rucklidge
Department of Applied Mathematics
University of Leeds
A.M.Rucklidge@leeds.ac.uk

Priya Subramanian, Jennifer Castelino
University of Leeds
P.Subramanian@leeds.ac.uk, cm13jkc@leeds.ac.uk

MS97

Predicting the Intraseasonal Precipitation Monsoon Through a Low-Order Nonlinear Stochastic Model with Intermittency

We assess the limits of predictability of the large-scale patterns in the boreal summer intraseasonal variability (BSISO) as a measure of precipitation. A recent developed nonlinear data analysis technique, nonlinear Laplacian spectrum analysis, is applied to the precipitation data, de?ning two spatial modes with high intermittency associated with the BSISO time series. A recent developed data-driven physics-constrained low-order modeling strategy is applied to these time series. The result is a 4-D system with two observed BSISO variables and two hidden variables involving correlated multiplicative noise through the nonlinear energy-conserving interaction. With the optimal parameters calibrated by information theory, the non-Gaussian fat tailed probability distribution functions, the autocorrelations and the power spectrum of the model signals almost perfectly match those of the observed data. An ensemble prediction scheme including an e?ective online data assimilation algorithm for determining the initial ensemble of the hidden variables shows the useful prediction skill is at least 30 days and even reaches 60 days in some years. The ensemble spread succeeds in indicating the forecast uncertainty. Twin experiment indicates the signi?cant skill of the model in determining the predictability limits of the BSISO. Finally, a practical spatial-temporal reconstruction strategy is developed and the predicted patterns have consistent skill as the time series.

Nan Chen
New York University
chennan@cims.nyu.edu

A Majda
NYU
jonjon@cims.nyu.edu

Sabeerali Thelliyil, Ajaya Ravindran
NYU Abu Dhabi
sabeer@nyu.edu, ajaya.mohan@nyu.edu

MS97

The Extreme Weather-Causing Patterns of the Midlatitudes

Identifying and understanding the dynamics of atmospheric circulation patterns that cause extreme events are crucial for better prediction and projection of weather extremes in the midlatitudes. Accurate linear response functions (LRFs) of global climate models (GCMs) can be used to overcome some problems related to studying the turbulent midlatitude circulation by providing a framework to control the turbulent flow for hypothesis testing, identify dynamical modes of the system, and evaluate statistical methods that can be applied to observational data [Hassanzadeh and Kuang 2015 GRL; Ma et al 2016 J. Atmos Sci.]. We compare and contrast LRFs calculated using Greens functions [Hassanzadeh and Kuang 2016 J. Atmos. Sci. Part I], Fluctuation-Dissipation Theorem, and Linear Inverse Modeling (LIM)/Dynamic Mode Decomposition (DMD) for an atmospheric GCM. We show how nonnormality of the LRF can complicate using the data-driven methods [Hassanzadeh and Kuang 2016 J. Atmos. Sci. Part II] and then employ the accurate LRF calculated using Greens functions to interpret the Principal Oscillatory Patterns obtained using LIM/DMD. The LIM/DMD is applied to the observational data from the Northern Hemisphere and the connection of the modes to extreme events such as heat waves and cold spells are discussed.

Pedram Hassanzadeh
Mechanical Engineering
Rice University
pedram@rice.edu

MS97

No Equations, No Parameters No Variables - Data and the Reconstruction of Normal Forms for Parametrically Dependent Dynamical Systems

Abstract Not Available At Time Of Publication.

Ioannis Kevrekidis
Dept. of Chemical Engineering
Princeton University
yannis@princeton.edu

MS97

Rogue Waves and Large Deviations in the Nonlinear Schroedinger Equation with Random Initial Data

The problem of appearance of rogue waves is investigated within the context of the modified nonlinear Schrödinger (MNLS) equation with random initial data. Specifically, we identify the initial condition within a random set of given statistics that is most likely to create a large disturbance of the solution of MNLS within a certain time. This allows us to estimate the probability of appearance of such disturbances, and to estimate the tail of the distribution of the solution amplitude. To make contact with real observations, we assume that the initial condition is Gaussian distributed, with a spectrum taken from experimental data. The method proposed builds on results from large deviation theory and is transportable to other deterministic dynamical systems with random initial conditions.

Eric Vanden-Eijnden, Tobias Grafke, Giovanni Dematteis
Courant Institute
New York University
eve2@cims.nyu.edu, grafke@cims.nyu.edu, dematteis@cims.nyu.edu

MS98

Bipolar Disorder Dynamics: Multiscale Mathematical Approaches for Translational Benefits

Bipolar disorder is a chronic, recurrent mental illness characterised by episodes of depressed and manic mood. Between these episodes, irregular mood fluctuations cause significant sickness and ill-health. In this talk I will introduce the paradigm of a mechanistic hierarchy to understand bipolar dynamics. This necessities the use of both multi scale mathematical (relaxation oscillations; Markov chains) and statistical (maximum likelihoods) approaches. I will emphasize the need for a cogent stochastic frameworks to advance the translational aspects of the work to achieve greater clinical benefits to these mathematical approaches to psychiatry.

Michael Bonsall
Dept. of Zoology
Oxford University
michael.bonsall@zoo.ox.ac.uk

MS98

Using Mathematical Models of Biological Processes in Genome-wide Association Studies of Psychiatric Disorders

Genome-wide association studies have implicated a large number of genes in psychiatric disorders such as bipolar disorder and schizophrenia. These genes, however, are usually weakly-associated and involved in diverse biological processes, thereby obscuring mechanisms for how such disorders arise. To better elucidate mechanisms, disorders can be tested for association with a set of genes that represent a biological pathway. Even so, mechanisms can remain elusive if ultimately a specific biological function is important. We propose and analyze a statistical test to implicate biological functions in psychiatric disorders. Our approach relies on mathematical models of biological processes to predict how strongly genes contribute to a certain biological function. These predictions are used to assign weights to genes, which are then incorporated into a statistical test on genetic data. To demonstrate, we use this statistical test to explore the role of calcium signaling in bipolar disorder.

Amy Cochran
Dept. of Mathematics
University of Michigan
alcochra@gmail.com

MS98

A Multiple Timescale Model of H-P-A Axis Dynamics: Onset, Timing, and Exposure Therapy of Stress Disorders

The hypothalamus-pituitary-adrenal (HPA) axis is a neuroendocrine system that regulates the secretion of the primary stress hormone called cortisol. We develop a delay equation model for HPA axis dynamics which distinguishes the slow and fast timescales that govern synthesis and secretion process in the hypothalamus. Analysis of our model demonstrates how bistability arises in certain parameter regimes, in which one of the two oscillating stable states is characterized as the "diseased" state. Identifying the most relevant parameters in shaping the bistable structure will provide insights on what determines the susceptibility of an individual to stress-related disorders. Moreover, understanding the underlying mechanisms of transitions between the two stable states can guide us in improving existing treatment protocols. In particular, our model explains how lower baseline cortisol level observed in PTSD subjects can be induced by the stress response elicited during a traumatic event in novel, intensity, and timing-dependent ways. Our model also suggests a mechanism whereby exposure therapy may act to normalize downstream dysregulation of the HPA axis associated with stress disorders such as PTSD.

Lae Un Kim
Dept. of Biomathematics
UCLA
laekim@gmail.com

Maria D'Orsogna
CSUN
dorsogna@csun.edu

Tom Chou
UCLA
Departments of Biomathematics and Mathematics
tomchou@ucla.edu

MS98

Modeling Neural Circuit Dysfunction in Schizophrenia: Effects of Disrupted Excitation-Inhibition Balance

Mechanistic understanding of mental disorders is limited by the stark explanatory gap between levels of analysis: disease-related mechanisms occur at the level of neurons and synapses, whereas symptoms occur at the level of cognition and behavior. I will present how biophysically-based computational modeling of neural circuits can be harnessed to probe how synaptic disruptions implicated in psychiatric diseases can induce alterations in cognition and large-scale neural network dynamics. In particular, I will discuss recent studies exploring the effects of disruption in the synaptic balance between excitation and inhibition, which is a leading hypothesis for cortical circuit dysfunction in schizophrenia.

John Murray
Yale University School of Medicine
john.murray@yale.edu

MS99

Complex Dynamics in a Conceptual Model of El Niño

ENSO (El Niño Southern Oscillation) is a climate phenomenon in the tropical Pacific ocean. Most of the time, upwelling in the eastern Pacific near South America makes ocean temperatures there cold and prevailing winds blow from east to west. At the end of some years, this pattern changes and produces global effects on the weather. This lecture will discuss the dynamics of a three dimensional vector field that has been proposed as a conceptual model of ENSO and its variability. Roberts et al. studied the model as a multiple time scale slow-fast dynamical system. This lecture will discuss its dynamics and some of the mathematical problems that have arisen in its analysis.

John Guckenheimer
Cornell University
jmg16@cornell.edu

MS99

Complex Action Potential Firing in Developing Inner Hair Cells

Inner Hair Cells (IHCs) are the proper receptor cells of hearing and are connected to the afferent nerves. In mammals, sound transduction by IHCs generates a receptor potential whose amplitude and phase drive auditory nerve firing. Immature IHCs differ in several aspects, and in particular in their electrophysiological characteristics and behaviour, from mature IHCs. Hence, from a functional perspective and to obtain insight into the development of hearing, it is important to understand the factors controlling the behavior of immature IHCs. In order to address this question we developed a mathematical model of electrical activity and calcium dynamics. Our model reproduces experimentally observed patterns of immature IHCs activity, such as spiking and bursting. Using the model we studied the involvement of intracellular calcium stores in regulating the intracellular calcium signal, important for local dynamic fine-tuning of the IHCs membrane filter. We also performed a numerical bifurcation analysis, which revealed the existence of a complex but structured set of periodic attractors with multiple-spike solutions. This is not surprising as often observed in models of excitable cells the variables in the immature IHCs model vary on different timescales. Given the multi-timescale character of our model we also employed fast-slow analysis with a view to investigate further the complex periodic behaviour of the model.

Krasimira Tsaneva-Atanasova
University of Exeter
k.tsaneva-atanasova@exeter.ac.uk

Daniele Avitabile
School of Mathematical Sciences
University of Nottingham
Daniele.Avitabile@nottingham.ac.uk

Harun Baldemir
Department of Mathematics
University of Exeter
h.baldemir@exeter.ac.uk

MS99

Generic Torus Canards and a Novel Class of Bursting Rhythms

Torus canards are solutions of slow/fast systems that alternate between attracting and repelling manifolds of limit cycles of the fast subsystem. Since their discovery in 2008, torus canards have been shown to mediate the transition from rapid spiking to bursting in several paradigm computational neural models. So far, torus canards have only been studied numerically, and their behaviour inferred based on classical averaging and geometric singular perturbation methods. This approach, however, is not rigorously justified since the averaging method breaks down near a fold of periodics – exactly where the torus canards originate. In this work, we combine techniques from Floquet theory, averaging theory and geometric singular perturbation theory to develop an averaging method for folded manifolds of limit cycles. In so doing, we devise an analytic scheme for the identification and topological classification of torus canards. We demonstrate the predictive power of our results in a model for hormone induced calcium oscillations in liver cells, where we use our torus canard theory to explain the mechanisms that underlie a novel class of bursting rhythms.

Theodore Vo
Boston University
theovo@bu.edu

MS99

Timescales and Mechanisms of Sigh-like Bursting and Spiking in Models of Rhythmic Respiratory Neurons

Neural networks generate a variety of rhythmic activity patterns, often involving different timescales. One example arises in the respiratory network in the preBötzinger complex of the mammalian brainstem, which can generate the eupneic rhythm associated with normal respiration as well as recurrent low-frequency, large-amplitude bursts associated with sighing. Two competing hypotheses have been proposed to explain sigh generation: the recruitment of a neuronal population distinct from the eupneic rhythm-generating subpopulation or the reconfiguration of activity within a single population. Here, we consider two recent computational models, one of which represents each of the hypotheses. We use methods of dynamical systems theory, such as fast-slow decomposition, averaging, and bifurcation analysis, to understand the multiple timescale mechanisms underlying sigh generation in each model. In the course of our analysis, we discover that a third timescale is required to generate sighs in both models. Furthermore, we identify the similarities of the underlying mechanisms in the two models and the aspects in which they differ.

Yangyang Wang
Mathematical Biosciences Institute
The Ohio State University
wang.9737@mbi.osu.edu

Jonathan E. Rubin
University of Pittsburgh
Department of Mathematics
jonrubin@pitt.edu

MS100

Unsteadily Manipulating Internal Flow Barriers

Typical flows contain internal flow barriers: specialized time-moving entities which demarcate distinct motions. Examples include the boundary between an oceanic eddy and a nearby jet, the edge of the Antarctic circumpolar vortex, or the interface between two fluids which are to be mixed together in an microfluidic assay. These barriers are Lagrangian in the sense that they move with the flow, and their location at each time is usually determined by performing diagnostic calculations using one of the many methods which are commonly referred to as Lagrangian Coherent Structure (LCS) analysis. The ability to control the locations of these barriers in a user-specified time-varying (unsteady) way can profoundly impact fluid transport between the coherent structures which are separated by the barriers. In this talk, the unsteady Eulerian velocity required to achieve a specified Lagrangian time-variation is explicitly derived. The excellent accuracy of the method is demonstrated using the Kelvin-Stuart cats-eyes flow and finite-time Lyapunov exponents. This is a promising first approach in the quest for being able to control internal flow barriers—and the transport across them—in general unsteady flows.

Sanjeeva Balasuriya
University of Adelaide
sanjeevabalasuriya@yahoo.com

MS100

Go With the Flow, on Jupiter and Snow, Coherence From Video Data Without Trajectories

Viewing a data set such as the clouds of Jupiter, coherence is readily apparent to human observers, especially the Great Red Spot, but also other great storms and persistent structures. There are now many different definitions and perspectives mathematically describing coherent structures, but we will take an image processing perspective here. We describe an image processing perspective inference of coherent sets from a fluidic system directly from image data, without attempting to first model underlying flow fields, related to a concept in image processing called motion tracking. In contrast to standard spectral methods for image processing which are generally related to a symmetric affinity matrix, leading to standard spectral graph theory, we allow a nonsymmetric affinity which arises naturally from the underlying arrow of time. We develop an anisotropic, directed diffusion operator corresponding to flow on a directed graph, from a directed affinity matrix developed with coherence in mind, and corresponding spectral graph theory from the graph Laplacian. Our examples will include partitioning the weather and cloud structures of Jupiter, and a local to Potsdam, N.Y. lake-effect snow event on Earth, as well as the benchmark test double-gyre system.

Erik Bollt
Clarkson University
bolltem@clarkson.edu

Abd Alrahman R. Almomani
Clarkson University
Department of Mathematics
almomaa@clarkson.edu

MS100

The Detection of Lagrangian Transport Structures in a Coral Reef Atoll: A Field Experiment

The flow circulation around coral ecosystems influence biological processes such as nutrient exchange and larval spawning, which determine population growth rates. Understanding reef connectivity is thus crucial to study population dynamics, as well as the resilience of coral reefs to the environmental stressors associated with climate change and other anthropogenic activities. Approaches from Lagrangian data analysis can provide useful information about the key transport structures that govern reef connectivity. In October 2016, we conducted a field experiment to test predictions of key Lagrangian Transport Structures in the vicinity of Scott Reef, an atoll system in the Timor Sea. From the surface velocity data obtained through a numerical ocean model, we ran predictive analysis and identified a strong,transient Lagrangian feature aligned with the spring tide. We deployed two arrays of surface drifters and demonstrated that this feature does indeed exist and govern the key transport characteristics of the region.

Margaux Filippi
Massachusetts Institute of Technology
Department of Mechanical Engineering
margaux@mit.edu

Alireza Hadjighasem
ETHZ
alirezah@ethz.ch

Matt Rayson, Gregory Ivey
University of Western Australia
matt.rayson@uwa.edu.au, greg.ivey@uwa.edu.au

Thomas Peacock
Massachusetts Institute of Technology
tomp@mit.edu

MS100

Phase Space Structures in Velocity Space for Gliding and Falling Bodies

Even the most simplified models of falling and gliding bodies provide rich nonlinear dynamical systems for study. A better understanding of such systems will give new insight into the biomechanics of animal gliders and the design of engineered systems such as descending spacecraft, supply airdrops, and robotic gliders. Taking a global view of the dynamics, we find an attracting invariant manifold that acts as a barrier to trajectories in velocity space. This invariant manifold presents a higher-dimensional analogue of terminal velocity onto which the dynamics of a glider settle. In this work, we present theoretical and numerical techniques for approximating the invariant manifold and discuss approaches to think about falling and gliding motion in terms of the underlying phase space structures. These phase space structures can be leveraged to design efficient control strategies for minimally actuated systems.

Gary K. Nave
Virginia Tech
Department of Biomedical Engineering and Mechanics
gknave@vt.edu

Isaac Yeaton
Virginia Tech
iyeaton@vt.edu

Shane D. Ross
Virginia Tech
Engineering Mechanics program
sdross@vt.edu

MS101

Continuous Data Assimilation for Geophysical Flows Employing Only Surface Measurements

We prove that data assimilation by feedback control can be achieved for the three-dimensional quasi-geostrophic equation using only large spatial scale observables on the dynamical boundary. On this boundary a scalar unknown (buoyancy or temperature of a fluid) satisfies the surface quasi-geostrophic equation. The feedback nudging is done on this 2D model, yet ultimately synchronizes the stream function of the three-dimensional flow. The main analytical difficulties involved in ensuring the synchronization property arise from the presence of a nonlocal dissipative operator in the surface quasi-geostrophic equation. This necessitates the derivation of various boundedness and approximation properties for the observation operators used in the feedback nudging.

Michael S. Jolly
Indiana University
Department of Mathematics
msjolly@indiana.edu

MS101

Connections Between Rate-Induced Tipping and Nonautonomous Stability Theory

We discuss the phenomenon of rate-induced tipping, where changing a parameter past a critical rate causes the system to 'tip' or diverge from an attractor, within the framework of nonautonomous stability theory. We explore rate induced tipping in several one dimensional model nonautonomous systems using finite time Lyapunov exponents and Steklov averages. Our results show that these numerical stability spectra are effective diagnostics for determining rate-induced tipping points in systems with parameters that are asymptotically constant or are linear. We then apply these stability spectra to a conceptual climate model.

Alanna Hoyer-Leitzel
Mathematics Department
Bowdoin College
ahoyerle@mtholyoke.edu

Alice Nadeau
University of Minnesota
nadea093@umn.edu

Andrew Roberts
Department of Mathematics
Cornell University
andrew.roberts@cornell.edu

Andrew J. Steyer
University of Kansas
asteyer@sandia.gov

MS101

Early-Warning Indicators for Rate-Induced Tipping

A dynamical system is said to undergo rate-induced tipping when it fails to track its quasi-equilibrium state due to an above-critical-rate change of system parameters. We study a prototypical model for rate-induced tipping, the saddle-node normal form subject to time-varying equilibrium drift and noise. We find that both most commonly used early-warning indicators, increase in variance and increase in autocorrelation, occur not when the equilibrium drift is fastest but with a delay. We explain this delay by demonstrating that the most likely trajectory for tipping also crosses the tipping threshold with a delay and therefore the tipping itself is delayed. We find solutions of the variational problem determining the most likely tipping path using numerical continuation techniques. The result is a systematic study of the most likely tipping time in the plane of two parameters, distance from tipping threshold and noise intensity.

Paul Ritchie
University of Exeter
Mathematics research Institute
pdlr201@exeter.ac.uk

MS101

A Nonautonomous Spectral Stability Theory for Ordinary Differential Initial Value Problem Solvers

In this talk we analyze the time-dependent Lyapunov stability of the numerical approximation of a time-dependent solution of an ordinary differential equation (ODE) initial value problem (IVP) by one-step and general linear methods. We give an example of an exponentially decaying, time-dependent, linear ODE for which an implementation of the implicit Euler method with adaptive step-size selection fails to produce a decaying numerical solution. To explain this phenomenon we employ Lyapunov and Sacker-Sell spectral theory to derive conditions under which the numerical solution of a bounded and uniformly exponentially stable trajectory of a nonlinear ODE IVP is bounded and uniformly exponentially stable. These results are used to develop a step-size selection strategy based on nonautonomous stability and accuracy.

Andrew J. Steyer
University of Kansas
asteyer@sandia.gov

Erik Van Vleck
Department of Mathematics
University of Kansas
erikvv@ku.edu

MS102

A Differential Equation with State-Dependent Delay Describing Stem Cell Maturation - Stability and Oscillations

The talk will be about a two component differential equation with implicitly defined state dependent delay and negative feedback. The equation describes the regulated maturation process of a stem cell population. In [Ph. Getto and M. Waurick, A differential equation with state-dependent delay from cell population biology, J. Diff. Eqs. 260 (7) 6176-6200, 2016] we have recently established smoothness conditions for the functional defining the right hand side such that theoretical results [H.O. Walther, The solution manifold and C^1-smoothness for differential equations with state-dependent delay, J. Diff. Eqs, 195 2003 46-65] can be applied to achieve well-posedness and a linearized stability theorem. Currently research topics include global existence, characteristic equations and oscillations via Hopf bifurcation and fixed point theorems. We are also applying pseudo spectral methods developed in [D. Breda, O. Diekmann,M. Gyllenberg, F. Scarabel and R. Vermiglio, Pseudospectral Discretization of Nonlinear Delay Equations: New Prospects for Numerical Bifurcation Analysis, SIAM J. Appl. Dyn. Syst. 15 (1) 1-23 2016, D. Breda, Ph. Getto, J. Sanchez Sanz and R. Vermiglio, Computing the Eigenvalues of Realistic Daphnia Models by Pseudospectral Methods SIAM J. Sci. Comp. 37 (6) (2015) A2607-A2629].

Philipp Getto
Bolyai Institute
University of Szeged
phgetto@yahoo.com

Dimitri Breda

Department of Mathematics and Computer Science
University of Udine
dimitri.breda@uniud.it

Gergely Rost
Bolyai Institute, University of Szeged
Szeged, Aradi vértank tere 1, H-6720 Hungary
rost@math.u-szeged.hu

Francesca Scarabel
University of Helsinki
Department of Mathematics and Statistics
francesca.scarabel@helsinki.fi

Tibor Krisztin
Bolyai Institute
University of Szeged
krisztin@math.u-szeged.hu

Istvan Balazs
University of Szeged
balazsi@math.u-szeged.hu

Yukihiko Nakata
Shimane University
Japan
yunayuna.na@gmail.com

MS102

Computing the Unstable Manifolds of Delay Differential Equations

In this talk I will discuss how one can compute high order Taylor approximations of the unstable manifold (of equilibrium and periodic solution) of a Delay Differential Equation. This approach is based on the Parametrization Method for ODEs and not only describes the unstable manifold, but also encapsulates the dynamics thereon. Finally, I will briefly sketch how the resulting parametrization can be made rigorous using a computer-aided proof.

Chris M. Groothedde
VU University Amsterdam
c.m.groothedde@vu.nl

MS102

Modelling Myelopoiesis with State-Dependent Delay Differential Equations

The production of white blood cells is modelled from hematopoietic stem cells (HSCs) through proliferating and maturing precursors to circulating neutrophils. The main cytokine that regulates this process is Granulocyte Colony Stimulating Factor (G-CSF). G-CSF regulates the differentiation rate of HSCs, the proliferation rate during mitosis, the maturation time, and the rate at which mature neutrophils are released into circulation from the bone marrow. We model the variable maturation time via an age-structured PDE model with variable ageing rate and show how this results in a model for myelopoiesis as a system of state-dependent delay differential equations. We discuss the application of this model to study dynamical diseases (cyclical neutropenia), infection immune response and peripheral blood stem cell harvesting and transplantation.

Tony R. Humphries
McGill University
Mathematics and Statistics
Tony.Humphries@mcgill.ca

MS102

Lyapunov-Razumikhin Techniques for State-Dependent Delay Differential Equations

We present theorems for the Lyapunov and asymptotic stability of the steady state solutions to general state-dependent delay differential equations (DDEs) using Lyapunov-Razumikhin methods. These theorems build upon the previous work of Hale and Verduyn-Lunel [Springer-Verlag, New York, 1993], and Barnea [SIAM J. Appl. Math, 17(4):681–697, 1969] which were mainly aimed at equations with simpler delay terms (e.g. constant and time-dependent delays), and are less applicable to state-dependent DDEs such as the following model equation,

$$\dot{u}(t) = \mu u(t) + \sigma u\big(t - a - cu(t)\big).$$

For fixed a and c, the stability region Σ_* of the zero solution to this model problem is known, and it is the same for both the constant delay ($c = 0$) and state-dependent delay ($c \neq 0$) cases. Using our results we can prove the asymptotic stability of the zero solution to this model problem in parts of Σ_*, considerably expanding upon the work of Barnea who proved Lyapunov stability for the simpler $\mu = c = 0$ constant delay case. Similar techniques are used to derive a condition for global asymptotic stability of the zero solution to the model problem, and bounds on periodic solutions when the zero solution is unstable.

Felicia Magpantay
Department of Mathematics
University of Manitoba
felicia.magpantay@gmail.com

MS103

Computation and Stability of Waves in Second Order Evolution Equations

The main topic of this talk are traveling waves for semilinear damped wave equations. We show how the freezing method generalizes from first to second order evolution equations by transforming the original PDE into a partial differential algebraic equation (PDAE). Solving a Cauchy problem via the PDAE generates a comoving frame, in which the profile varies as little as possible, and an algebraic variable which approximates its speed. Under suitable stability conditions the profile and the speed converge to their limiting values. A rigorous theory of this effect is presented in one space dimension, building on recent results by J. Rottmann-Matthes on nonlinear stability of waves in first order hyperbolic systems. Numerical examples demonstrate the applicability of the method. We also show generalizations of the method to rotating waves in several space dimensions. For this case the nonlinear stability theory is still largely unexplored.

Wolf-Juergen Beyn
Bielefeld University
beyn@math.uni-bielefeld.de

Simon Dieckmann, Christian Doeding
Department of Mathematics
Bielefeld University
simon.dieckmann@uni-bielefeld.de, cdoeding@math.uni-

bielefeld.de

MS103

Defect Induced Target Waves in Reaction Diffusion Systems

It is known that in reaction diffusion systems the phase modulation of coherent structures is modeled by a viscous eikonal equation. Using this phase equation we show the existence of target waves in reaction diffusion systems in $\mathbb{R}^2$, which are generated by the presence of a localized perturbation (the defect). Viewed from the point of view of perturbation theory this problem presents two difficulties: it is a perturbation problem beyond all orders, and moreover the linear operator has a zero eigenvalue embedded in the essential spectrum. The first technical difficulty is overcome using techniques from matched asymptotics, while the second hurdle is surpassed using the Fredholm properties of the Laplacian in the setting of Kondratiev spaces and a decomposition of these spaces into polar modes. Similar results have been shown using spatial dynamics in the radially symmetric case, and the theory of Schrödinger operators in the non-radial case. The novelty of this approach is that this technique is also applicable to integro-differential equations, where the linearization is now a radially symmetric convolution operator.

Gabriela Jaramillo
The University of Arizona
gjaramillo@math.arizona.edu

MS103

Spectral Stability of Solutions to the Vortex Filament Hierarchy

The Vortex Filament Equation (VFE) is part of an integrable hierarchy of filament equations. Several equations in this hierarchy have been derived to describe vortex filaments in various situations. Inspired by these results, we develop a general framework for studying the existence and the linear stability of closed solutions of the VFE hierarchy. The framework is based on the correspondence between the VFE and the nonlinear Schrödinger (NLS) hierarchies. Our results establish a connection between the AKNS Floquet spectrum and the stability properties of the solutions of the filament equations. We apply our machinery to solutions of the filament equation associated to the Hirota equation. We also discuss how our framework applies to soliton solutions.

Stephane Lafortune
College of Charleston
Department of Mathematics
lafortunes@cofc.edu

Thomas Ivey
College of Charleston
iveyt@cofc.edu

MS103

Stability of PT Symmetric Ground States for Schrodinger and Klein-Gordon Equations in Higher Space Dimensions

We consider $\mathcal{PT}$ Schrödinger and Klein-Gordon equations in higher dimensional spaces. After the construction of the ground states, we proceed to systematically and completely characterize their spectral stability. This extends, in the Schrödiner case, the recent results of Alexeeva, Barashenkov, Sukhorukov, Kivshar and Bludov, Konotop, Malomed. In our analysis, we rely exclusively on instability index counting methods.

Milena Stanislavova
University of Kansas, Lawrence
Department of Mathematics
stanis@math.ku.edu

MS104

Dynamical Proxies of North Atlantic Predictability and Extremes

Atmospheric flows are characterized by chaotic dynamics and recurring large-scale patterns. These two characteristics point to the existence of an atmospheric attractor defined by Lorenz as: the collection of all states that the system can assume or approach again and again, as opposed to those that it will ultimately avoid. The average dimension D of the attractor corresponds to the number of degrees of freedom sufficient to describe the atmospheric circulation. However, obtaining reliable estimates of D has proved challenging. Moreover, D does not provide information on transient atmospheric motions, such as those leading to weather extremes. Using recent developments in dynamical systems theory, we show that such motions can be classified through instantaneous rather than average properties of the attractor. The instantaneous properties are uniquely determined by instantaneous dimension and stability. Their extreme values correspond to specific atmospheric patterns and match climate extreme events.

Davide Faranda
LSCE, CEA Saclay l'Orme des Merisiers, CNRS
davide.faranda@lsce.ipsl.fr

MS104

The Extremal Index for the AR(1) Process: Finite Size Considerations

I begin by discussing a few heuristic interpretations of the extremal index, namely (i) a measure of loss of iid degrees of freedom, (ii) the multiplicity of a compound Poisson point process, (iii) the sojourn time of an excursion. I then consider finite-size effects of the extremal index in the AR(1) process with Gaussian noise which, as the sample size goes to infinity, shows no clustering.

Nicholas Moloney
London Mathematical Laboratory
n.moloney@lml.org.uk

MS104

Stochastic Bifurcation in Random Logistic Maps

A topological bifurcation point of stochastic dynamics is introduced illustrating noise-induced chaos in a random logistic map. We identify two different transition points characterized by the zero-crossing points of the supremum of the dichotomy spectrum and the Lyapunov exponent. The associated three phases are characterized as a random periodic attractor, a random point attractor, and a random strange attractor, respectively. The dichotomy spectrum characterizes uniform hyperbolicity of random attractors based on all possible asymptotic behaviour, while the Lyapunov exponent characterizes stability of random attractors based on the most likely asymptotic behaviour. A solvable example of noise-induced bifurcation and an example of numerically computed dichotomy spectrum for the random logistic map are presented as well.

Yuzuru Sato
RIES/Department of Mathematics
Hokkaido University
ysato@math.sci.hokudai.ac.jp

MS104

Extreme Value Theory in Dynamical Systems

We present in this note a new application of Extreme Value Theory (EVT) to Coupled Lattice Maps (CLM) on a finite lattice. Actually a first result in this direction was given in the paper, where the authors considered two coupled interval maps and applied their theory of rare events for open systems with holes to investigate the first entrance of the two components into a small strip along the diagonal, which is equivalent to the synchronisation of the two-side network up to a certain tolerance. We will show that that synchronisation process could be interpreted and quantified by computing the asymptotic distribution of the maximum of a suitable random process.

Sandro Vaienti
CPT Marseille
vaienti@cpt.univ-mrs.fr

MS105

Nonlinear Dynamics of Inner Ear Hair Cells

The inner ear constitutes a remarkably sensitive biological detector. The first step in auditory processing is performed by hair cells, which act as transducers that convert minute mechanical vibrations into electrical signals that can be sent to the brain. The hair cells operate in a viscous environment, but can nevertheless sustain oscillations and amplify incoming signals. The thermodynamic requirements indicate the presence of an underlying active process that pumps energy into the system. We explore experimentally the response of oscillatory hair bundles to signals spanning a broad range of frequencies and amplitudes, to study their phase-locking properties. We demonstrate the presence of Arnold Tongues, with significant overlaps between the synchronization regimes. Secondly, we demonstrate the presence of chaos in the innate motility exhibited by hair cell bundles. Poincare maps constructed from driven bundle oscillations indicate a quasiperiodic transition from chaos to order with increasing amplitude of mechanical forcing. The onset of this transition is accompanied by an increase in mutual information between the stimulus and the hair bundle, indicative of signal detection. Finally, we explore the interaction between active bundle mechanics and the electrical circuit comprised of somatic ion channels, and measure the impact of this coupled system on the overall detection performed by the hair cell.

Dolores Bozovic, Justin Faber, Yuki Quinones, S. W. F. Meenderink
UCLA
bozovic@physics.ucla.edu, jfaber3@ucla.edu, yukiq@ucla.edu, swfmeenderink@ucla.edu

Michael Levy
Weizmann Institute
michael.levy@weizmann.ac.il

MS105

Signal Detection by Active, Noisy Oscillators on the Brink of Self-Oscillation

Many physical systems employ limit-cycle oscillators to detect periodic signals, but their performance is often limited by noise. For example, vertebrate hearing is based on the mechanosensory hair bundle that detects sound-induced vibrations within the ear. We study the response of noisy oscillators operating near supercritical or subcritical Hopf bifurcations to periodic forcing. A noisy oscillators frequency-detuned sensitivity and degree of entrainment, as well as its bandwidth are maximized when it self-oscillates near a Hopf bifurcation. Owing to three distinct mechanisms, the sensitivity and entrainment of a Hopf oscillator peak as a function of the noise level. We confirmed several of these predictions experimentally by periodically forcing hair bundles held near the two types of Hopf bifurcation. We describe how to determine the identity and location of a bifurcation from observations of a bundles displacement. A hair bundle is most sensitive and most easily entrained by a periodic stimulus when it spontaneously oscillates near a Hopf bifurcation. Moreover, the addition of noise can improve a bundles ability to detect the stimulus. This work suggests that auditory systems rely on self-oscillatory elements operating near a Hopf bifurcation.

Daibhid O Maoileidigh, Joshua Salvi, AJ Hudspeth
The Rockefeller University
dmelody@rockefeller.edu, jsalvi@rockefeller.edu, hudspaj@rockefeller.edu

MS105

Nonlinear Micromechanics of the Organ of Corti in the Low-Frequency Region of the Cochlea

The organ of Corti in the mammalian inner ear houses the mechanosensitive inner and outer hair cells. Outer hair cells can provide mechanical forces that can amplify a weak sound stimulus, which is then detected by the inner hair cells. However, the micromechanics of how mechanical amplification is achieved by the organ of Corti remains unclear. In particular, the apical organ of Corti is shaped differently from the basal organ, indicating a different micromechanical functioning that remains poorly understood. Here we combine mathematical modeling and laser-interferometric recordings to show that the apical organ of Corti's micromechanics contains a strong nonlinearity with respect to length changes of the outer hair cells. This nonlinearity allows the organ of Corti to operate as an electromechanical transistor: the elongation of the outer hair cells can sensitively regulate how much sound stimulation is transmitted to the inner hair cells. These results could, for instance, explain how stimulation of the inner hair cells can be regulated by efferent nerve fibers.

Tobias Reichenbach
Imperial College
London
reichenbach@imperial.ac.uk

Nikola Ciganovic
Imperial College London
n.ciganovic13@imperial.ac.uk

Rebecca Warren, Batu Keceli

University of Linköping
rebeccalouwarren@gmail.com, batu.keceli@liu.se

Stefan Jacob
Karolinska Institute
stefan.jacob@ki.se

Anders Fridberger
University of Linköping
anders.fridberger@liu.se

MS105

Symmetries and Asymmetries in Cochlear Mechanics

A symmetry is something that stays the same when something else changes. Identifying symmetries in data can provide powerful constraints on models. In this talk, I review a handful of important symmetries (and non-symmetries) evident in responses from the mammalian cochlea and discuss their consequences for models of cochlear mechanics.

Christopher Shera
University of Southern California
christopher.shera@gmail.com

MS106

Bifurcation of Nonlinear Bound States from Eigenvalues and from Spectral Intervals in PT-symmetric Systems

In PT-symmetric nonlinear systems, like the Gross-Pitaevskii equation with a complex PT-symmetric potential, bound states with real propagation constants (i.e. standing solitary waves) have been previously found numerically. We present a rigorous proof of their bifurcation in two important cases: bifurcation from a simple eigenvalue and from a spectral interval. In the case of the bifurcation from a simple real linear eigenvalue we work in the general abstract setting

$$A\psi - \epsilon f(\psi) = \lambda\psi,$$

with $\epsilon \in \mathbb{R}$ (small), a Lipschitz continuous f and with a closed linear operator A densely defined on a Hilbert space and having a non-empty resolvent set. In the more difficult case of the bifurcation from a spectral interval we consider the one dimensional stationary Gross-Pitaevskii (GP) equation

$$-\psi' + V(x)\psi + \sigma(x)|\psi|^2\psi = \lambda\psi,\ x \in \mathbb{R}$$

with periodic PT-symmetric coefficients V and σ. We provide explicit asymptotic expansions of the bound states with error estimates. The proofs rely in both cases on the Banach fixed point theorem restricted to a symmetric subspace. In the case of the periodic GP equation we work in Bloch variables.

Tomas Dohnal
TU Dortmund
tomas.dohnal@math.tu-dortmund.de

Dmitry Pelinovsky
McMaster University
Department of Mathematics
dmpeli@math.mcmaster.ca

Petr Siegl
University of Bern, Switzerland
siegl@math.unibe.ch

MS106

Faster and More Accurate Computations for Certain Highly Oscillatory Wave Problems

As we can see in many optical applications, faster and more accurate solution approximations of highly oscillating problems, including solutions of partial differential equations and beam integrals, are tasks with an overarching importance. However, they are widely perceived as an extremely difficult or challenging issue in physics computations. In fact, a successful numerical method must base on an appropriate discretization which overcomes the oscillation. Once the dynamics of a computational strategy is designed and correctly understood, the problem of highly oscillatory quadratures may become relatively simple and that the precision of calculations may even increase as the frequency of oscillation grows. This talk will focus at a monochromatic laser traveling in a linear medium with refractive index that varies slowly on the scale of an optical wavelength. Several interesting numerical methods will be introduced and discussed for evaluating corresponding highly oscillatory wave problems. Some simulation results will be given.

Qin Sheng
Department of Mathematics
Baylor University
Qin_Sheng@baylor.edu

MS106

Nonlinear Dynamics of Parity-tme (PT) Symmetric Lasers

The introduction of parity-time symmetry formalism lead to the discovery of new and unimaginable phenomena in optics. The first $\mathcal{PT}$ laser was introduced a few years ago. The new experiments have gained substantial attention from the theoretical point of view. Current models are limited to the lasing in the steady-state regime or under assumption of stationary population inversion. In this work, we propose a study of both spatial and temporal dynamics of the two coupled micro-ring $\mathcal{PT}$ symmetric resonators. The proposed models were obtained from the basic equations of the semi-classical laser theory.

Alexey Sukhinin
Southern Methodist University
asukhini@uvm.edu

Jianke Yang
Department of Mathematics and Statistics
University of Vermont
jyang@cems.uvm.edu

MS106

Long-time Dynamics and Interaction of Ultrashort Light Pulses

The propagation dynamics and interaction of ultrashort light pulses is presented. The pulse propagation behavior is studied by numerical simulations of mathematical models at realistic physical conditions. The spatiotemporal dynamics of ultrashort light pulses within dispersive equations like generalized (3+1)D nonlinear Schrodinger equation and (3+1)D nonlinear envelope equations as governing equations as well as at ionization free and ionization regimes is revealed and summarized. The complex structure and the presence of terms with different physical sense requires the coordinate splitting to be preceded by splitting by physical factors (processes). In contrast to the coordinate splitting this kind of splitting can be exact in some nodes and in the intervals it can be controlled. We show that this method is relevant for study of propagating ultrashort localized pulses in nonlinear waveguides. The nonintegrability of the considered dynamical systems and the missing exact solutions requires to provide the investigation only numerically. The obtained results are reliable and give good predictions for the material quantities and dynamics of the light pulses.

Michail Todorov
Faculty of Applied Mathematics and Informatics
Technical University of Sofia, Bulgaria
mtod@tu-sofia.bg

MS107

Hankel Alternative View Of Koopman (Havok) Analysis of Chaotic Systems

Understanding the interplay of order and disorder in chaotic systems is a central challenge in modern quantitative science. Toward this goal, approximate linear representations for nonlinear dynamics have been long sought, driving considerable interest in modern Koopman operator theory. We present a universal, data-driven decomposition of chaos as an intermittently forced linear system. This work combines delay embedding and Koopman theory to decompose chaotic dynamics into a linear model in the leading delay coordinates with forcing by low energy delay coordinates; we call this the Hankel alternative view of Koopman (HAVOK) analysis. This analysis is applied to the Lorenz system, as well as to real-world examples such as the Earth's magnetic field reversal, and data from ECG, EEG, and measles outbreaks. In each case, the forcing statistics are non-Gaussian, with long tails corresponding to rare events that trigger intermittent switching and bursting phenomena; this forcing is highly predictive, providing a clear signature that precedes these events. The activity of the forcing signal demarcates large coherent regions of phase space where the dynamics are approximately linear, from those that are strongly nonlinear. Video abstract: https://youtu.be/831Ell3QNck

Steven Brunton, Bingni W. Brunton
University of Washington
sbrunton@uw.edu, bbrunton@uw.edu

Joshua L. Proctor
Institute for Disease Modeling
JoshLProctor@gmail.com

Eurika Kaiser
University of Washington
eurika@uw.edu

Nathan Kutz
University of Washington
Dept of Applied Mathematics
kutz@uw.edu

MS107

A Toolbox for Computing Spectral Properties of Dynamical Systems

In this talk, I will introduce a toolbox to compute spectral properties of the Koopman operator for measure-preserving dynamical systems. The algorithm is based on a periodic approximation of the underlying dynamical system. Convergence results are briefly discussed and results are presented for certain well-known systems.

Nithin Govindarajan
University of California, Santa Barbara
ngovindarajan@engineering.ucsb.edu

MS107

Network Identification Based on Koopman Operator Theory

Spectral characterization and global linearization of nonlinear systems are two key features of the Koopman operator framework. These two aspects can be used to derive efficient numerical methods for studying nonlinear systems. This is for instance the case in the context of network identification, i.e. the problem of inferring the structure of a network from measurements of its collective dynamics. We propose two novel techniques for network identification based on the Koopman operator framework: (1) spectral network identification method and (2) lifting method. (1) Spectral network identification. We show that there is a relationship between the spectrum of the Koopman operator (which is measured from the network dynamics) and the spectral properties of the network (Laplacian spectrum). Then, by inferring these spectral properties, the method makes possible the use of a few local measurements to uncover global topological properties of the network (e.g. average node degree). (2) Lifting method. This method is based on the key idea that, instead of identifying a nonlinear system in the state space, we can lift the data to a higher-dimensional space and identify the linear Koopman operator. This lifting technique is a general nonlinear systems identification method and, in particular, provides an efficient numerical scheme to infer the topology and the dynamics of (possibly large) networks.

Alexandre Mauroy
University of Liege
alexandre.mauroy@unamur.be

MS107

Koopman Operator Framework for Nonlinear Time Series Analysis

We introduce a Koopman operator based framework for nonlinear time-series analysis, a field which relies heavily on nonlinear dynamical systems theory for characterization of (typically univariate) irregular time series data. Spectral properties of infinite dimensional but linear Koopman operator are exploited as a means for nonlinearly decomposing, enhancing and analyzing the measured signals. We demonstrate our framework in variety of time series applications including forecasting, anomaly detection, indexing/retrieval and classification, and for distinguishing causality from correlation.

Amit Surana
System Dynamics and Optimization
United Tecnologies Research Center (UTRC)

suranaa@utrc.utc.com

MS108

Filament Tension and Phase Locking of Meandering Scroll Waves

Rotating spiral waves are often not rigidly rotating, but exhibit a quasi-periodic motion known as 'meander'. Examples include cardiac tissue and the Belousov-Zhabotinsky chemical reaction. Using response function theory, we derive the drift equations for meandering spiral waves and apply it to the important cases of electroforetic drift (in chemical media) and curvature-induced motion of 3D scroll waves. We show that only under certain conditions (when averaging is possible), the emerging filament tension property is found. Otherwise, phase-locking effects or more complex behaviour is found. For a given external field strength, we discuss the behaviour of the parallel and perpendicular drift velocities in the parameter space of Barkley's model including the meandering region.

Hans Dierckx
Department of Physics and Astronomy
Ghent University
hans.dierckx@ugent.be

MS108

The Role of Conduction Block in Spiral Breakup and Merger

Spiral wave chaos in excitable media, such as cardiac tissue, is characterized by continuous breakups and mergers of spiral wave segments. While the linear instabilities of traveling waves leading up to wave breakup in different models are not universal, the breakup itself proceeds in a universal fasion. It involves conduction block, where a portion of the wave fails to propagate, creating two new spiral cores. We show that this process can be described quantitatively by following the dynamics of two level sets which define the excitation front and the trailing edge of a refractory region of a preceding wave. Quite surprisingly, we find that spiral wave mergers, where two spiral cores of opposite chirality merge and annihilate, also involve conduction block and can be understood with the help of the same two level sets. Hence, the two key phenomena responsible for maintaining spiral chaos both involve a universal physical mechanism and allow a universal topological description.

Roman Grigoriev
Georgia Institute of Technology
Center for Nonlinear Science & School of Physics
roman.grigoriev@physics.gatech.edu

Christopher Marcotte
Georgia Tech
christopher.marcotte@physics.gatech.edu

MS108

Scroll Wave Drift and Interaction in Excitable Systems with Height Variations

The Belousov-Zhabotinsky (BZ) solution spontaneously self-organizes three-dimensional vortices, analogous to natural phenomena like ventricular tachycardia and *Dictyostelium discoideum* aggregation. Sharp edges and corners affect the dynamics of these excitation vortices. We test earlier theoretical predictions regarding the vortex drift velocity and find excellent agreement over a large range of geometric parameters; however, the underlying asymptotic theory fails for deep systems. We also report the behavior of dense vortex populations in systems with periodic height variations. All of these findings are obtained from a bubble-free BZ reaction.

Dayton Syme
Department of Chemistry & Biochemistry
Florida State University
dsyme@chem.fsu.edu

Oliver Steinbock
Department of Chemistry and Biochemistry
Florida State University
steinbck@chem.fsu.edu

MS108

Periodic Sequence of Stabilized Wave Segments in Excitable Media

Wave segments represent an interesting and important example of spatio-temporal pattern formation in a broad class of nonlinear dynamic systems, so-called excitable media. They have been observed, for instance, in cardiac tissue, concentration waves in thin layers of the Belousov-Zhabotinsky reaction or during cell aggregation of Dictyostelium discoideum. For a given excitability a medium supports propagation of a wave segment with a selected size and shape, which is intrinsically unstable. In order to make this solution observable it has to be stabilized by an adequate noninvasive feedback control. For the case of a solitary propagating wave segments a universal selection rules have been found by use a free-boundary approach. The main aim of our study is to generalize these results on a case of a periodic sequence of wave segments. To this aim the motion of a stabilized wave segment is numerically studied by use of a generic reaction-diffusion model with nonlinear activator-inhibitor kinetic. In addition, the free-boundary approach is applied to determine the wave segment shape and the speed as functions of the medium parameters. We hope that the results obtained in this study are also applicable to the spiral wave dynamics.

Vladimir Zykov
Max Planck Institute for Dynamics and Self-Organization
vladimir.zykov@ds.mpg.de

Eberhard Bodenschatz
Max Planck Institute for Dynamics & Self-Organization
eberhard.bodenschatz@ds.mpg.de

MS109

Fisher-Kpp Invasion Fronts on Homogeneous Trees and Random Networks

We study the dynamics of the Fisher-KPP equation on the infinite homogeneous tree and Erdős-Réyni random graphs. We assume initial data that is zero everywhere except at a single node. For the case of the homogeneous tree, the solution will either form a traveling front or converge pointwise to zero. This dichotomy is determined by the linear spreading speed and we compute critical values of the diffusion parameter for which the spreading speed is zero and maximal and prove that the system is linearly determined. We also study the growth of the total population in the network and identify the exponential growth rate as a function of the diffusion constant. Finally, we make predictions for the Fisher-KPP equation on Erdős-Rényi random graphs based upon the results on the homogeneous tree. We observe that exponential growth rates on the random network can be bounded by growth rates on the homogeneous tree and provide an explanation for the sub-linear exponential growth rates that occur for small diffusion.

Matt Holzer
Department of Mathematics
George Mason University
mholzer@gmu.edu

Aaron Hoffman
Franklin W. Olin College of Engineering
aaron.hoffman@olin.edu

MS109

Contagion Shocks in a Model of Panicking Crowds

We consider an agent-based model of emotional contagion coupled with motion that has previously been studied in the computer science community. The model involves movement with speed proportional to a fear' variable that undergoes a temporal consensus averaging with other nearby agents. We study the effect of Riemann initial data for this problem in 1D, leading to shock dynamics that are studied both within the agent-based model as well as in a continuum limit. We examine the model under distinguished limits as the characteristic contagion interaction distance and the interaction timescale both approach zero. Here, we observe a threshold for the interaction distance vs. interaction timescale that produces qualitatively different behavior for the system - in one case particle paths do not cross and there is a natural Eulerian limit involving nonlocal interactions and in the other case particle paths can cross and one may consider only a kinetic model in the continuum limit. We will also discuss recent extensions of the model to two dimensions, and new methods of efficient computation for the model.

Martin Short
Georgia Tech
mbshort@math.gatech.edu

MS109

On the Evolution of Cancerous Cells

Recent advances on a nonlinear model for tumor growth will be discussed.

Konstantina Trivisa
University of Maryland
Department of Mathematics
trivisa@math.umd.edu

MS109

Travelling Wave Solutions for a Model of Tumour Invasion

A recent study by Korolev et al. [Nat. Rev. Cancer, 14:371–379, 2014] evidences that the Allee effectin its strong form, the requirement of a minimum density for cell growthis important in the spreading of cancerous tumours. We present one of the first mathematical models of tumour invasion that incorporates the Allee effect. Based on analysis of the existence of travelling wave solutions to this model, we argue that it is an improvement on previous models of its kind. We show that, with the strong Allee effect, the model admits biologically relevant travelling wave solutions, with well-defined edges. Furthermore, we uncover an experimentally observed biphasic relationship between the invasion speed of the tumour and the background extracellular matrix density. This is joint work with Lotte Sewalt, Kristen Harley and Sanjeeva Balasuriya

Peter van Heijster
Mathematical Sciences School
Queensland University of Technology
petrus.vanheijster@qut.edu.au

Lotte Sewalt
Leiden University
lotte@math.leidenuniv.nl

Kristen Harley
Queensland University of Technology
ke.harley@student.qut.edu.au

Sanjeeva Balasuriya
University of Adelaide
sanjeevabalasuriya@yahoo.com

MS110

Optimal Experimental Design for Extreme Event Statistics in Nonlinear Dynamical Systems

We propose a computational strategy for the fast evaluation of extreme event statistics associated with nonlinear dynamical systems. In particular, our goal is the development of a computational algorithm that adaptively provide a series of experimental parameters that rapidly leads to the accurate determination of the probability density function (pdf) for an arbitrary quantity of interest. Since, our goal is to capture extreme event statistics, emphasis is given on the accuracy of the method with respect to the tails of the pdf. The algorithm is based on the blending of i) an inexpensive, low-fidelity model, which is assumed to accurately capture average behavior of the dynamical system, but not necessarily extreme events, ii) a Gaussian process regression framework which blends information from the experiment and the low-fidelity model, and iii) a probabilistic decomposition synthesis method that provides an efficient representation of the pdf and its tail structure. The combination of these three components allows for estimation of the pdf and its tail structure, as well as the computation of upper and lower bounds. From an initial set of experiments, we adaptively select additional sample points (experimental parameters) so that the posterior distance between the estimated upper and lower bounds of the pdf is minimized. We illustrate the method to several examples of various complexity.

Mustafa Mohamad
MIT
mmohamad@mit.edu

Themistoklis Sapsis
Massachusetts Institute of Techonology
sapsis@mit.edu

MS110

Predicting Extreme Events for Passive Scalar Turbulence in Two-Layer Baroclinic Flows through Reduced-Order Stochastic Models

The capacity of imperfect reduced-order models to capture crucial tracer statistical features such as tracer energy spectrum and tracer intermittency is investigated. The passive scalar field is advected by a two-layer baroclinic turbulent flow in atmosphere and ocean regimes with jets and vortices. Much simpler and more tractable linear Gaussian stochastic models are proposed to approximate the complex and high-dimensional advection flow field. The imperfect models prediction skill are improved through a judicious calibration about the model errors in autocorrelation function using the leading order statistics of the background advection flow field, while no additional prior information about the passive tracer statistics is required. A systematic framework of measuring the autocorrelation function with empirical information theory is introduced, and optimal model parameters under this unbiased information measure can be achieved in a training phase before the prediction. It is demonstrated that the prediction skill of the imperfect model can be effectively improved through the calibration strategy with optimal parameters. Crucially leading order statistical quantities like the tracer energy spectrum and fat-tails in the tracer density functions in the most important large scales can be captured efficiently with accuracy using the reduced-order tracer model in various dynamical regimes of the flow field with distinct statistical structures.

Di Qi
New York University
qidi@cims.nyu.edu

A Majda
NYU
jonjon@cims.nyu.edu

MS110

Identification and Protection Against Critical Contingencies in Power Systems

Power system is the largest, and arguably the most complex machine ever built by humans. Due to inherent nature of power flows, power system lacks global stability and is naturally fragile. Large enough disturbances may cause the loss of stability and trigger the cascading failures resulting in major blackouts. Aggressive introduction of renewable generation increases the overall stress of the system, so the stability constraints will likely become the main barrier for transition to clean energy sources. Despite many decades of research, stability assessment is still the computational bottleneck in power grid operation process. Modern tools from optimization and dynamical systems provide a unique opportunity for addressing these problems with new generation of fast and reliable algorithms. This talk will review the computational challenges the power system operators face today and propose specific strategies for characterization of transient stability and impact of uncertainty for better screening of critical contingencies and design of corrective remedial actions.

Konstantin Turitsyn
Massachusetts Institute of Technology
turitsyn@mit.edu

MS110

Trajectory Stratification for Rare Event Simulation

I will outline a general mathematical framework for trajectory stratification of stochastic processes based on the nonequilibrium umbrella sampling method. Trajectory stratification involves decomposing trajectories of the underlying process into fragments limited to restricted regions of state space (strata), computing averages over the distributions of the trajectory fragments within the strata with minimal communication between them, and combining those averages with appropriate weights to yield averages with respect to the original underlying process. The result is an efficient and robust scheme for very general rare event simulation problems. Our framework reveals the full generality and flexibility of trajectory stratification, and it illuminates a common mathematical structure shared with the highly successful, equilibrium umbrella sampling method for free energy calculations.

Jonathan Weare
University of Chicago
Department of Statistics and the James Franck Institute
weare@uchicago.edu

MS111

Data-Driven Parameterization of the Generalized Langevin Dynamics for Bio-Molecules

This talk is concerned with microscopic models for biomolecules. Due to the overwhelming number of degrees of freedom in an all-atom model, coarse-grained description has become a more promising candidate for simulating important biological processes. We present a data-driven approach to determine the parameters in a generalized Langevin model, which in principle can be derived from the full dynamics using the Mori-Zwanzig projection formalism. We make explicit connections between the parameters and the statistics of the coarse-grain variables. Several examples will be shown to demonstrate the effectiveness of the algorithm.

Xiantao Li
Department of Mathematics
Pennsylvania State University
xli@math.psu.edu

MS111

Data-Driven Modeling and the Mori-Zwanzig Formalism

In many scientific and engineering applications, a fully-resolved computational model is either unavailable (due to missing measurements or poorly-understood physics) or prohibitively expensive to use. Data-driven modeling methods are thus valuable for constructing effective models, by combining relevant physics with data. In this talk, I will provide a brief introduction to data-driven modeling and model reduction, touching on relevant theoretical and practical issues. I will then discuss a key issue, namely how to represent the memory effects that arise when a dynamical system is projected onto a subset of its degrees of freedom. Connections to the Mori-Zwanzig projection operator formalism of nonequilibrium statistical mechanics will be discussed.

Fei Lu
Department of Mathematics, UC Berkeley
Mathematics group, Lawrence Berkeley National Laboratory
flu@lbl.gov

Kevin K. Lin
Department of Mathematics
University of Arizona
klin@math.arizona.edu

Alexandre Chorin

Department of Mathematics
University of California at Berkeley
chorin@math.berkeley.edu

MS111

Renormalization and Stability of Coarse-Grained Models

The construction of reduced order (coarse-grained) models for complex systems has been a very active area of research in recent years. We will present results about the effect of the dimensionality of the original (full order) system on the stability and accuracy of reduced order models. In particular, we want to emphasize that the inability to simulate the full order system can cause instabilities for the reduced order models and how renormalization can be used to tame such instabilities.

Panos Stinis
Pacific Northwest National Laboratory
panagiotis.stinis@pnnl.gov

MS111

Dimension Reduction for Systems with Slow Relaxation

Dynamical systems that relax very slowly to equilibrium and can encode long term memory, i.e. the influence of the initial conditions can persist. We develop reduced, stochastic models for high dimensional dynamical systems with slow relaxation. We present a variety of empirical and first principles approaches for model reduction, and build a mathematical framework for analyzing the reduced models. We introduce the notions of *universal* and *asymptotic* filters to characterize 'optimal' model reductions. We discuss how our methods apply to the practically important problem of modeling oil spills.

Shankar C. Venkataramani
University of Arizona
Department of Mathematics
shankar@math.arizona.edu

Raman Venkataramani
Seagate Technologies
ramanv@ieee.org

Juan M. Restrepo
Oregon State University
Department of Mathematics
restrepo@math.oregonstate.edu

MS112

Unstable Behavior in Capitalistic Economic Systems

We present a simple extension of the well-known Solow model of economic growth that describes the statistical behavior of business cycle fluctuations observed in the U.S. Gross Domestic Product (GDP). The extension shows how the network structure of economic supply chains induces a positive feedback loop in macrodynamics that causes the GDP to be very sensitive to small random disturbances in consumption and investment. The model suggests that recessions are inevitable in any well developed capitalistic economic system and that increasing globalization of the world economy will result in economic expansions and contractions that are less likely to be locally confined and more likely to affect economies on a global scale.

Jim Brannan
Department of Mathematical Sciences
Clemson University
jrbrn@clemson.edu

MS112

Tipping Point Analysis of Dynamical Systems, with Applications in Geophysics and Environmental Sciences

We apply tipping point analysis for anticipation, detection, and forecast of tipping points in a dynamical system. Degenerate fingerprinting indicator is a dynamically derived lag-1 autocorrelation (or short-range scaling exponent of Detrended Fluctuation Analysis [Livina and Lenton, GRL 2007]), which monitors memory in a series for early warning signals. Potential analysis detects a tipping point at the time when it happens, which is illustrated in a contour plot mapping the potential dynamics of the system [Livina et al, Climate of the Past 2010; Livina et al, Climate Dynamics 2011; Livina et al, Physica A 2012; Livina et al, Physica A 2013]. Potential analysis is also used to forecast time series by extrapolation of Chebyshev approximation coefficients of the kernel distribution, with reconstruction of correlations in the data [Livina et al, Physica A 2013]. The methodology has been tested on artificial data and on geophysical, ecological and industrial sensor datasets [Livina et al, Journal of Civil Structural Health Monitoring, 2014; Kefi et al, PLoS ONE 2014; Livina et al, Chaos 2015; Perry et al, Smart Materials and Structures, 2016], and proved to be applicable to trajectories of dynamical systems of arbitrary origin [Vaz Martins et al, PRE 2010].

Valerie N. Livina
National Physical Laboratory
valerie.livina@npl.co.uk

MS112

Stochastic Dynamics of Near-Surface Winds over Land

Understanding the variability of near-surface winds is important for computing surface fluxes, for characterizing extreme wind events, and for assessing the wind power resource. Over land surfaces, the probability distribution of near-surface wind speed displays a marked diurnal evolution. In the bottom few tens of meters of the atmosphere, mean wind speeds at night tend to be weaker than during the day - but the tails of the nocturnal distribution are much longer than those of the day. In this talk, I will provide evidence that the highly-skewed nature of nocturnal surface wind speeds is related to the existence of two distinct regimes of the stably stratified nocturnal planetary boundary layer. An empirical stochastic model will be developed using a Hidden Markov Model analysis of long observations of wind and temperature at a tall tower at Cabauw, in the Netherlands. The relationship between regime structure and the surface wind speed probability distribution will also be investigated using an idealized stochastic representation of the near-surface momentum budget.

Adam Monahan
University of Victoria

monahana@uvic.ca

MS112

Metastable Phenomena in a Dynamical System with a Discontinuous Vector Field: Case of Amazonian Vegetation Model

For the tipping elements in the Earth's climate system, the most important issue to know is how stable the desirable state is against random, possibly non-small perturbations. We report the results of the stability analysis of the metastable fertile forest state in stochastically perturbed Amazonian Vegetation (AV) model with discontinuous vector field. To solve the problem of non-uniqueness of solutions, that often rise in this type of systems with repulsive sliding mode, the discontinuous vector field, employing the mollification method, was approximated by a smoothened drift coefficient. Relying on the empirical evidence that the environmental studies provide, we have included in the AV system the symmetric α-stable Lévy perturbations. In our stability analysis we employ mean firs exit time (MFET), escape probability (EP) and stochastic basin of attraction (SBA) which are the quantities that describe the dynamical behavior of the system and usually used in the investigation of the metastable states. Our main conclusions are that the slightest threat to the forest state stability represents Lévy noise with big jumps of the small intensity ($\alpha = 0.5$, $\alpha = 1$ and $\varepsilon = 0.1$). On the other hand, a Lévy noise with small jumps ($\alpha = 1.5$) as well as noise with high intensity ($\varepsilon = 1$, $\alpha = 0.5$ or $\alpha = 1$) significantly accelerate the transition between forest and savanna states causing the high instability of the forest.

Larissa I. Serdukova
School of Mathematics and Statistics,
Huazhong University of Science and Technology
larissa.serdukova@docente.unicv.edu.cv

MS113

Exact Model Reduction by a Slow-Fast Decomposition of Multi-Degree-of-Freedom Vibrations

We discuss conditions under which a general nonlinear mechanical system can be exactly reduced to a lower-dimensional model that involves only the most flexible degrees of freedom. This Slow-Fast Decomposition (SFD) enslaves the stiff degrees of freedom exponentially fast to the flexible ones while trajectories converge to a slow manifold. We also find that near equilibria, the SFD gives a mathematical justification for two modal-reduction methods used in structural dynamics: static condensation and modal derivatives. These formal reduction procedures, however, are also found to return incorrect results when the SFD conditions do not hold. We illustrate all these results on mechanical examples.

George Haller
ETH, Zurich, Switzerland
georgehaller@ethz.ch

Sten Ponsioen
ETH Zurich
Switzerland
stenp@ethz.ch

MS113

Model Reduction to Spectral Submanifolds for Forced Beams: An Infinite-Dimensional Analysis

We use invariant manifold results on Banach spaces to conclude the existence of spectral submanifolds (SSMs) in a class of nonlinear, externally forced beam oscillations . Reduction of the governing PDE to the SSM provides an exact low-dimensional model which we compute explicitly. This model captures the correct asymptotics of the full, infinite-dimensional dynamics. Our approach is general enough to admit extensions to other types of continuum vibrations. The model-reduction procedure we employ also gives guidelines for a mathematically self-consistent modeling of damping in PDEs describing structural vibrations.

Florian Kogelbauer
ETH Zurich, Switzerland
kogelbauer@mavt.ethz.ch

MS113

Random Perturbations of Periodically Driven Nonlinear Oscillators: Homogenization and Large Deviations

The recent surge of research articles in energy harvesting focuses on the "cantilever beam" devices which are used to convert small amplitude mechanical vibration into electrical energy that could be used for electronic devices with low power requirements. Prototypical beam type nonlinear energy harvesting models contain double well potentials, external or parametric periodic forcing terms, damping and ambient broadband additive noise terms. This talk will develop a unified approach to study the dynamics of single degree of freedom systems excited by both periodic and random perturbations. The phase space for a periodically driven nonlinear oscillator consists of many resonance zones. The near resonant dynamics of such systems, in the presence of weak noise, is not well understood. We will study this problem in depth with the aim of discovering a common geometric structure in the phase space and determining the effect of weak noise on the escape from a resonance zone. We obtain the large-deviation rate function for the escape by developing an asymptotic method based on averaging and large deviations.

Navaratnam Sri Namachchivaya, Nishanth Lingala
UIUC
navam@illinois.edu, lingala1@illinois.edu

Ilya Pavlyukevich
Institut für Stochastik
Friedrich–Schiller–Universität Jena, Germany
ilya.pavlyukevich@uni-jena.de

MS113

Nonlinear Model Identification and Spectral Submanifolds for Multi-Degree-of-Freedom Mechanical Vibrations

In a nonlinear oscillatory system, spectral submanifolds (SSMs) are the smoothest invariant manifolds tangent to linear modal subspaces of an equilibrium. Amplitude-frequency plots of the dynamics on SSMs provide the classic backbone curves sought in experimental nonlinear model identification. We develop here a methodology to compute analytically both the shape of SSMs and their corresponding backbone curves from a data-assimilating model fitted to experimental vibration signals. Using examples of both synthetic and real experimental data, we demonstrate that this approach reproduces backbone curves with high accuracy.

Robert Szalai
University of Bristol
r.szalai@bristol.ac.uk

MS114

Biological Aggregation Driven by Social and Environmental Factors: A Nonlocal Model and Its Degenerate Cahn-Hilliard Approximation

Biological aggregations such as insect swarms and fish schools may arise from a combination of social interactions and environmental cues. Nonlocal continuum equations are often used to model aggregations, which manifest as localized solutions. While popular in the literature, the nonlocal models pose significant analytical and computational challenges. Beginning with the nonlocal aggregation model of [Topaz, Bertozzi & Lewis, Bull. Math. Bio., 2006], we derive the minimal well-posed long-wave approximation, which is a degenerate Cahn-Hilliard equation. Using analysis and computation, we study energy minimizers and show that they retain many salient features of those of the nonlocal model. Furthermore, using the Cahn-Hilliard model as a testbed, we investigate how an external potential modeling food sources can suppress peak population density, which is essential for controlling locust outbreaks. Random potentials tend to increase peak density, whereas periodic potentials can suppress it.

Andrew J. Bernoff
Harvey Mudd College
Department of Mathematics
ajb@hmc.edu

Chad M. Topaz
Dept. of Mathematics, Statistics, and Computer Science
Macalester College
ctopaz@macalester.edu

MS114

Traveling Waves and Breathers in An Excitatory-Inhibitory Neural Field

Neural fields are spatially-extended nonlinear integrodifferential equations that represent the large-scale dynamics of populations of neurons mediated by synaptic interactions and other neuronal processes (e.g., firing rate adaptation and synaptic depression) and support a wide range of spatiotemporal dynamics, including traveling waves. We study the existence and stability of traveling waves of localized activity in a two-population E-I neural field which governs the interaction between excitatory and inhibitory neurons along a one-dimensional spatial domain. We develop existence conditions for activity bumps traveling with constant speed and derive an Evans function to analyze their spectral stability. We show that drift bifurcations of stationary bumps serve as a mechanism for generating traveling bump solutions in the E-I neural field as parameters are varied. Furthermore, we explore the interrelations between stationary and traveling types of bumps and breathers (time-periodic oscillatory bumps) by bridging together analytical and simulation results for stationary/traveling bumps and their bifurcations in a region in parameter space. Interestingly, we find evidence for a codimension 2 drift-Hopf bifurcation and show that the codim 2 point serves as an organizing center for the dynamics of these four types of spatially-localized solutions.

Stefanos Folias
Department of Mathematical Sciences
University of Alaska Anchorage
sfolias@alaska.edu

MS114

Patterns and Waves in a Spatially-Extended Neural Field Model

Cortical waves have been observed in a variety of neural circuit experiments. These events of activity have important features such as velocity and phase relations which impact the termination and propagation of neural activity. In this talk, we analyze traveling waves occurring in a 1D spatially-distributed Wilson-Cowan firing rate model to better understand how the system transitions from traveling fronts to pulses as the time constant of inhibition increases ($\tau > 0$). The traveling front represents an increase from down to up-state activity, while the traveling pulse reflects a wave of excitation that returns to down-state activity. As τ increases, the system passes through a Hopf bifurcation and limit cycles emerge. Here, the front leads to spatially-homogeneous (bulk) oscillations, while further increasing τ pushes the oscillation through a period-doubling bifurcation, and the front leads to spatiotemporal patterns. The instability to the bulk oscillation makes for interesting dynamics near the transition to a pulse solution, and for a small range of τ-values, the system shows a traveling front that tends to a spatiotemporal pattern or a traveling pulse, depending on the stimulus duration.

Jeremy D. Harris
Department of Mathematics
University of Pittsburgh
jdh71@pitt.edu

MS114

Compositional Evolution of Quasi-bilayers in the Symmetric Two-component Functionalized Cahn-Hilliard Equation

Multicomponent mixtures in general support bilayers with a diversity of lipid compositions. We study a strong two-component FCH model with a radial symmetric potential which admits a family of quasi-bilayers with various compositional ratios between amphiphile A and B. In the absence of pearling bifurcation, the compositional and geometric evolution of quasi-bilayers decouples, in the sense that the former evolution takes place in the $1/\epsilon$ time scale when the normal velocity of the interface is still zero. More specifically, the composition ratio satisfies a nonlocal equation accommodating rich dynamics. Depending on the competition between the phase separation and the quenching of the background, the composition ratio evolves into, (1) a homogeneous profile; (2) a phase separation profile where the bilayer consists of pure A regions and pure B regions; or, (3) a quenched profile in a co-dim two manifold. In case (2) and (3), a rapid spatial variation of the composition ratio promotes surface diffusion terms from lower orders. While the evolution of phase separation profiles mimics Allen-Cahn type coarse graining, novel dynamics emerges from the evolution of rapid varying profiles in a neighborhood of the quenched manifold: the compositional profile stays nearby the quenching manifold and evolves into a periodic profile with a large period.

Qiliang Wu, Keith Promislow

Michigan State University
qwu@math.msu.edu, kpromisl@math.msu.edu

MS115

Rhinovirus: From Biochemistry and Immunology to Families and Communities

Rhinoviruses have been described as the perfectly adapted virus, and have striking features ranging from enormous serotype diversity to low virulence and immunogenicity. Models that combine the full complexity of the immune response with the idiosyncracies of transmission, such as strong age and symptom dependence, would be impossible to parameterize or analyze. I will present a series of models of rhinovirus, starting within hosts and stepping up to families and communities, showing how we can extract the key aspects of each level of organization to feed into the next level to begin to explain the striking features of rhinovirus. I will apply these results to examine the many connections between rhinovirus and asthma, perhaps the most important clinical effect of this virus, and consider the possible consequences of the newly proposed vaccine.

Fred Adler
University of Utah
Dept. of Mathematics, Dept. of Biology
adler@math.utah.edu

MS115

Examining Signatures of Within-Host Malaria Heterogeneity at an Epidemiological Level

Plasmodium falciparum, the most virulent human malaria parasite, matures via asexual reproduction within the human host, but undergoes sexual reproduction within its vector host, the *Anopheles* mosquito. Consequently, the mosquito stage of the parasite life cycle provides an opportunity to create novel parasite genetic information in mosquitoes infected with multiple parasite populations, altering parasite diversity at the population level. Despite the important implications for disease transmission and malaria control, a quantitative mapping of diversity generation within the vector is lacking. To examine the role that vector biology plays in modulating parasite diversity, we develop a multi-scale model that estimates the diversity as a consequence of different bottlenecks and expansion events occurring during the parasite life cycle and couples the diversity development within the mosquito to transmission to humans. For the underlying framework, we use a stochastic model of within-vector *P. falciparum* dynamics and simulate the dynamics of infections with multiple distinct parasite populations. We use the results of the within-vector portion of our model to inform transmission of the parasites to the human population. Our model quantitatively maps parasite diversity through the life cycle of the parasite including bottlenecks between the mosquito and the human host.

Lauren Childs
Virginia Polytechnic Institute and State University
lchilds@vt.edu

Olivia Prosper
University of Kentucky
olivia.prosper@uky.edu

MS115

The Role of Multi-Scale Selection in the Emergence of Drug Resistance

Recent experimental work has shown how drug treatment can cause competitive release of drug resistant strains within an infected individual. How this competitive release at the within-host scale translates into the spread of drug resistance through a population, however, is less clear. I will present a mathematical model that integrates the processes occurring at multiple scales during the emergence and spread of drug resistance. Analysis of the model shows that, although competitive release can enhance the spread of resistance within a host, processes operating at the between-host scale can nevertheless curtail the spread of resistance.

Troy Day
Departments of Mathematics & Biology
Queen's University, Kingston, Canada
tday@mast.queensu.ca

Johanna Hansen
Department of Mathematics and Statistics
Queen's University
johannah@mast.queensu.ca

MS115

Emerging Disease Dynamics in a Model Coupling Within and Between-Host Systems

Epidemiological models and immunological models have been studied largely independently. However, the two biological processes (within- and between-host interactions) occur jointly and models that couple the two processes may generate new biological insights. We developed and analyzed ODE models that link an SI epidemiological model and an immunological model for pathogen-cell dynamics. When the two sub-systems are considered in isolation, dynamics are standard and simple. That is, either the infection-free equilibrium is stable or a unique positive equilibrium is stable depending on the whether the relevant reproduction number is less or greater than 1. However, when the two sub-systems are dynamically coupled, the full system exhibits more complex dynamics including backward bifurcations; that is, multiple positive equilibria exist with one of which being stable even when the reproduction number is less than 1. The biological implications of such bifurcations are illustrated using an example concerning the spread and control of toxoplasmosis.

Zhilan Feng
Department of Mathematics
Purdue University
zfeng@math.purdue.edu

MS116

Recent Advances in Rigorous Computation of the Evans Function

For a wide class of physical systems of interest, asymptotic orbital stability of traveling waves is determined by spectral stability. For many systems, analytical techniques determine spectral properties in various limits, but are unable to treat the entire space of solutions. In these cases, numerical studies are used to provide strong evidence of spectral properties. Our recent work deals with rigorous verification of spectral stability by controlling all error, including machine truncation error, in these numerical computations. In this talk we describe recent advances in rigorous computation of the Evans function, an analytic function whose zeros determine spectral stability of the underlying traveling wave.

Blake Barker
Brown University
blake@math.byu.edu

Kevin Kevin Zumbrun
Indiana University
USA
kzumbrun@indiana.edu

MS116

The Gray-Scott Model: Bistable Regime

Using singularly perturbed nature of the Gray-Scott model, we apply multi-scale analysis in a systematic way to show the existence and stability of a traveling front and a traveling pulse. While the traveling front is stable, the pulse is unstable.

Vahagn Manukian
Miami University Hamilton
manukive@miamioh.edu

MS116

Center Manifolds for a Class of Degenerate Evolution Equations and Existence of Small-Amplitude Kinetic Shocks

We construct center manifolds for a class of degenerate evolution equations including the steady Boltzmann equation and related kinetic models, establishing in the process existence and behavior of small-amplitude kinetic shock and boundary layers. Notably, for Boltzmann's equation, elements of the center manifold are shown to decay in velocity at near-Maxwellian rate, in accord with the formal Chapman-Enskog picture of near-equilibrium flow as evolution along the manifold of Maxwellian states, and Grad's 13-moment approximation via Hermite polynomials in velocity.

Alin Pogan
Miami University
Department of Mathematics
pogana@miamioh.edu

MS116

Complex Bifurcations in Benard-Marangoni Convection

We report a stability analysis of an idealized model of Benard-Marangoni convection in two spatial dimensions. We show that more complicated bifurcations can appear in this system for a certain nonlinear temperature profile as compared to bifurcations in the classical Rayleigh-Benard and Benard-Marangoni systems with simple linear vertical temperature profiles. The obtained results lead to our understanding of complex spatial patterns at a free liquid surface and will be useful for turbulence theory.

Ivan Sudakov
University of Dayton
Department of Physics
isudakov1@udayton.edu

Sergey Vakulenko
Russian Academy of Sciences
Institute for Problems in Mechanical Engineering
vakulenfr@gmail.com

MS117

A First Step Toward Quantifying the Climates Information Production Over the Last 68,000 Years

We take an information-theoretic approach to analyzing 68 thousand years of water isotope data from the WAIS Divide ice core, the longest continuous and highest-resolution record yet recovered from Antarctica. The water isotopes are primarily a proxy for local temperature at the time of snow deposition, but also contain information about broader atmospheric circulation patterns. Using a well defined depth-age scale, we apply weighted permutation entropy to calculate the Shannon entropy rate of the isotope measurements. We find that the rate of information production reveals differences in analytical techniques, even when those differences leave no visible traces in the raw data. The entropy calculations also allow us to identify a number of intervals in the data that may be of direct relevance to paleoclimate interpretation. To validate the results, we perform a number of statistical tests, particularly whether the information production arises from climatic signals or post-processing of the ice after recovery from the drill site.

Joshua Garland
University of Colorado at Boulder
joshua@santafe.edu

Tyler Jones
University of Colorado at Boulder
INSTAAR
tyler.jones@colorado.edu

Elizabeth Bradley
University of Colorado
Department of Computer Science
Elizabeth.Bradley@Colorado.EDU

Ryan G. James
University of California, Davis
rgjames@ucdavis.edu

James White
University of Colorado at Boulder
INSTAAR
james.white@colorado.edu

MS117

Overview of the Boundary Layer, Cyclones, and the Dynamics Involved

An introduction to atmosphere physics will be given as a prelude to the other talks in this mini-symposium. Specifically, we'll introduce the atmospheric boundary layer, and what is means to be stably stratified. Turbulence will be discussed in the context of atmospheric dynamics, and an overview of extra-tropical cyclones will be given.

David Collins
Vancouver Island University
david.collins@viu.ca

MS117

Dynamics of the Stably Stratified Atmospheric

Boundary Layer

Flow, stratification, and turbulence in the atmospheric boundary layer are dynamically coupled: turbulent intensity and fluxes are influenced by the the eddy-averaged state, which itself depends on the turbulent fluxes. This interplay is of particular interest in the stably stratified boundary layer, which is observationally found to exist in distinct regimes (respectively very and weakly stably stratified). This talk will present recent observational and idealized modelling results regarding these regimes and the transitions between them. While the models considered are highly idealized from a meteorological perspective, they are highly nonlinear dynamical systems with a large number of degrees of freedom. Equilibrium and linear stability analyses will be presented and compared with time-dependent model behaviour. The relation of these model results to the observed structures of boundary layer regimes will also be discussed.

Amber Holdstworth
SEOS, University of Victoria
amberholdsworth@gmail.com

Adam Monahan
University of Victoria
monahana@uvic.ca

MS117

The Dissipation Structure of Extratropical Cyclones

The physical characteristics of extratropical cyclones are investigated based on non-equilibrium thermodynamics. Non-equilibrium thermodynamics (developed mostly in the 1970-90) has been widely used in many scientific fields. Non-equilibrium thermodynamics can reveal the dissipation structure for any thermodynamic and dynamic system. It is found that dissipation is always present in an extratropical cyclone, and the dissipation center is not always coincident with the low pressure center. This is especially for true for young cyclones. The different components of internal entropy production correspond to different dissipation processes. Usually, the thermal dissipation due to turbulent vertical diffusion and convection lags geographically behind the dynamic dissipation, and this is due to wind stress. At the incipient stage, the dissipation is mainly thermal in nature. A concept of temperature shear is introduced as the result of thermal dissipation. The temperature shear provides a useful diagnostic for extratropical cyclone identification. We present results from a regional study in the western Pacific.

Jiangnan Li
Environment and Climate Change Canada
jiangnan.li@canada.ca

MS118

The Signal and the Noise: Microfluidics and Sensing in the Cochlea

The nonlinear and finely tuned response of the organ of Corti of the mammalian cochlea to external acoustic stimulation serves to induce a radial fluid flow in the sub-tectorial space (STS) and over the inner hair cell (IHC) hair bundle (HB). In turn, this flow gives rise to forces on the HB that are transduced into neural impulses at the synaptic pole of the cell. The free-standing IHC HBs responsible for transducing the acoustic signal are immersed in the 2-5 μm thick viscous fluid layer filling the STS. This is a surprising evolutionary development as the thermoviscous noise engendered by such positioning might result in an ineffective sensor. In order to understand the trade-off between noise and sensitivity at the IHC HB, we developed a model of the fluid-structure interaction between the viscoelastic structures and the viscous STS and sulcus fluids. We used the fluctuation dissipation theorem to compute the thermoviscous noise forces and a stochastic model of the channel to estimate the gating noise force. Using this model we found the noise induced rms HB tip motion of less than a few nanometers (less than the expected threshold levels) and that the channel noise is the dominant noise at the apex while viscous noise is the dominant at the base. We also computed the minimal detectable signals associated with shear motion of the tectorial membrane along with the effect of HB channel gating and adaption on thresholds.

Karl Grosh, Aritra Sasmal
University of Michigan
grosh@umich.edu, asasmal@umich.edu

MS118

Effect of Electro-Mechanical Coupling on Stochastic Oscillations in a Model of Hair Cells

Hair cells are mechanoreceptors which transduce mechanical vibrations to electrical signals in peripheral organs of senses of hearing and balance in vertebrates. Somatic cell motility and active motility of the hair bundle, mechanically sensitive structure on the hair cell apex, are two main mechanisms by which hair cells can amplify mechanical stimuli. In amphibians and some reptiles active processes in hair cells result in noisy mechanical oscillation of hair bundles, which may lead to frequency selective amplification. The same cells often demonstrate spontaneous electrical oscillation of their somatic potentials, a signature of yet another amplification mechanism. Functional role of voltage oscillation is not well understood. We use computational modeling to study how the interaction of two distinct unequally noisy oscillators, mechanical and electrical, may affect their spontaneous dynamics, battle noise, and shape sensitivity of hair cells to external mechanical signals.

Alexander Neiman
Ohio University
Department of Physics and Astronomy
neimana@ohio.edu

Rami Amro
Department of Physics
University of California Los Angeles
ramro@physics.ucla.edu

MS118

From Passive to Active Mechanics in the Cochlea

Active mechanics in the cochlea, known as cochlear amplification, refers to the outer hair cell (OHC) based forcing that enhances mechanical responses to sound. Responses to a particular frequency are only enhanced over a limited spatial region, where that frequency peaks in the passive cochlea. Thus, the cochlear amplifier increases the sharpness of cochlear frequency tuning, explaining why external hearing aids are limited in their ability to compensate for hearing loss. The mechanism for localized amplification was explored with synchronous measurements of basilar membrane motion and OHC electrical responses. These measurements revealed a phase shift of voltage relative to displacement, occurring at the frequency for which mechanical enhancement began. Consideration of the known OHC voltage-force relationship showed that the phase shift introduces the force-velocity phasing needed for power transfer from OHCs to the cochlear traveling wave. The phase shift was independent of stimulus level and thus seems to be based in the cochleas passive mechanics. Ongoing measurements of cochlear motion and voltage explore the basis for the phase shift that activates cochlear amplification, and to determine if it is altered in unhealthy cochleae. The cochlear amplifier is a key, yet fragile element of auditory processing. Understanding the reason for its fragility is closely tied with understanding the operation of the healthy cochlea.

Elizabeth S. Olson
Columbia University
eao2004@columbia.edu

MS118

Local and Spatially Extended Frequency Locking: Distinguishing Between Additive and Parametric Forcing

The auditory system displays remarkable sensitivity and frequency discrimination, attributes shown to rely on an amplification process that involves a mechanical as well as a biochemical response. Models that display proximity to an oscillatory onset (a.k.a. Hopf bifurcation) exhibit a resonant response to distinct frequencies of incoming sound, and can explain many features of the amplification phenomenology. To understand the dynamics of this resonance, frequency locking is examined in a system near the Hopf bifurcation and subject to two types of driving forces: additive and parametric. Derivation of a universal amplitude equation that contains both forcing terms enables a study of their relative impact on the hair cell response. In the parametric case, although the resonant solutions are 1:1 frequency locked, they show the coexistence of solutions obeying a phase shift of π, a feature typical of the 2:1 resonance. Different characteristics are predicted for the transition from unlocked to locked solutions, leading to smooth or abrupt dynamics in response to different types of forcing. The theoretical framework provides a more realistic model of the auditory system, which incorporates a direct modulation of the internal control parameter by an applied drive. The above seems to have fundamental implications to spatially localized resonances that known to arise in the cochlea.

Arik Yochelis
Jacob Blaustein Institutes for Desert Research,
Ben-Gurion University
yochelis@bgu.ac.il

Yuval Edri
Ben-Gurion University of the Negev
yuvaled@post.bgu.ac.il

Dolores Bozovic
UCLA
bozovic@physics.ucla.edu

MS119

Instability of Steep Ocean Waves and Whitecapping

Wave breaking in deep oceans is a challenge that still defies complete scientific understanding. Sailors know that at wind speeds of approximately 5m/sec, the random looking windblown surface begins to develop patches of white foam (whitecaps) near sharply angled wave crests. We idealize such a sea locally by a family of close to maximum amplitude Stokes waves and show, using highly accurate simulation algorithms based on a conformal map representation, that perturbed Stokes waves develop the universal feature of an overturning plunging jet. We analyze both the cases when surface tension is absent and present. In the latter case, we show the plunging jet is regularized by capillary waves which rapidly become nonlinear Crapper waves in whose trough pockets whitecaps may be spawned.

Sergey Dyachenko
Brown University
sergey_dyachenko@brown.edu

Alan Newell
University of Arizona
Department of Mathematics
anewell@math.arizona.edu

MS119

Time-delay Models of Multi-mode Laser Dynamics

Delay differential equations (DDE) model of a passively mode-locked semiconductor laser was first proposed as an alternative to semiclassical Maxwell-Bloch equations and simplified complex Ginzburg-Landau-type (CGL) Haus master equation of mode-locking as well as single-mode ODE models. While these DDE models retain all the most important dynamical characteristics of multi-mode semiconductor lasers that can be observed directly in Maxwell-Bloch equations, they can be also studied using the perturbation analysis tools similarly to ODEs or CGL-type equations and using asymptotic and numerical bifurcation analysis methods. In particular, they proved to be useful for qualitative explanation and prediction of the experimentally observed phenomena for passively mode-locked lasers under the effects of external periodic forcing and noise. In the last few years, multi-mode DDE models found application in spatially extended systems such as broad-area lasers under off-axis feedback, frequency-swept sources (Fourier domain mode-locked lasers) and lasers under long optical feedback used for generation of temporally localized structures. Cavity of a FDML laser contains very long optical fiber that causes strong chromatic dispersion. The effect of chromatic dispersion can be described using a distributed delay term in the laser model, which can lead to the appearance of modulational instability and temporal dissipative solitons. We discuss our recent results and feature challenges.

Alexander Pimenov
Weierstrass Institute
alexander.pimenov@wias-berlin.de

Andrei G. Vladimirov
Weierstrass Institute for Applied Analysis and Stochastics
Berlin, Germany
vladimir@wias-berlin.de

MS119

Estimation of Timing Jitter in a Delayed Differen-

tial Model of Semiconductor Laser

We consider a delay differential model of a passively mode locked semiconductor laser proposed by A. Vladimirov and D. Turaev. The system exhibits a stable periodic solution, which models a periodic train of light pulses in the mode locked regime. Timing jitter is the variation of the time interval between the pulses induced by noise. Assuming small additive noise, we derive an asymptotic expression for the diffusion coefficient of the phase diffusion, which quantifies the jitter. Asymptotic formulas are compared to simulation results.

Dmitry Rachinskiy
Department of Mathematical Sciences
University of Texas at Dallas
dxr124030@utdallas.edu

MS119

Generation of Broadband Chaotic Light and Its Applications in Detection and Communication

Chaotic light has attracted widespread attention in recent years because of its important applications, for instance, in encrypted communications, physical random number generation, lidar, and time domain reflectometry. And a semiconductor laser with optical feedback is usually the common choice to generate chaotic light owing to its simple and integratable setup. However, the chaos bandwidth is limited by the laser relaxation oscillation to a few GHz. In order to take full advantage of bandwidth, we proposed a series of methods to generate broadband chaotic light including optical injection into a laser diode with feedback, dual-wavelength injection into a FP-LD with feedback, incoherent delayed self-interference of a chaotic laser, fiber ring resonator seeded by a chaotic laser, and optical heterodyning of chaotic lasers. Using above mentioned methods, chaotic light with bandwidth ranging from 14 GHz to 32 GHz can be readily achieved. Having achieved broadband chaotic light, we applied it to free space ranging and fiber fault location of communication networks. In both applications, the high spatial resolution of a few centimeters can be achieved since the wide bandwidth of chaotic light. Furthermore, we expanded the broadband chaotic light to chaos-based communication and secure key distribution. Results indicate that broadband chaotic light enables Gbit/s data transmission satisfying the requirement of current high-speed optical communication.

Longsheng Wang, Anbang Wang, Tong Zhao, Yuanyuan Guo, Daming Wang
Taiyuan University of Technology
Institute of Optoelectronic Engineering
wls1034@link.tyut.edu.cn, wanganbang@tyut.edu.cn, zhaotong.tyut@aliyun.com, guoyuanyuan815@163.com, wangdaming0910@link.tyut.edu.cn

Yuncai Wang
Taiyuan University
Institute of Optoelectronic Engineering
wangyc@tyut.edu.cn

MS120

An Equal Space, An Equal Time: Data-Driven Embeddings of Complex Dynamics

We present a way to embed nonlinear phenomena based on their intrinsic variability. In particular we apply diffusion maps, a non- linear dimensionality reduction method, to extract useful axes from measurements or simulation data of different non-linear phenomena. Useful hereby refers to the degree of coarsening in which we want to observe our system, with this degree being specified by appropriately tuning the kernel scale in the diffusion maps approach. In addition, we demonstrate that these axes are, provided we have sufficient data, in- dependent of the particular nature of the measurement entity. As illus- trative examples, we apply our method on spatio-temporal chaotic dy- namics apparent in the complex Ginzburg-Landau equation, on mod- ulated traveling waves in the Kuramoto-Sivashinksy equation and on chimera states, states of coexisting coherence and incoherence. For the latter, we show that it is possible to extract insightful order parame- ters, allowing further understanding of these intricate dynamics. In addition, this embedding can be done invariant to the measurement function, showing similarities to the Koopman operator.

Ioannis Kevrekidis
Dept. of Chemical Engineering
Princeton University
yannis@princeton.edu

Felix Kemeth
Technische Universität München
felix@kemeth.de

MS120

Optimal Parameter Selection for Extended Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) is one of mode decomposition methods using the theory of Koopman operator, which considers latent dynamics of time series data. Recently, in order to more accurately approximate nonlinear latent dynamics, an extended DMD has been proposed [M. Williams et al., 2015]. In this study, we propose a method for optimal parameter selection in the extended DMD, and show that we can improve the estimation accuracy of Koopman modes.

Wataru Kurebayashi, Sho Shirasaka
Tokyo Institute of Technology
wkurebayashi@gmail.com, shirasaka.s.aa@m.titech.ac.jp

Hiroya Nakao
Graduate School of Information Science and Engineering,
Tokyo Institute of Technology
nakao@mei.titech.ac.jp

MS120

Comparison of Dynamic Mode Decomposition, Koopman Mode Decomposition, and Vector Prony Analysis

Dynamic Mode Decomposition (DMD) has since its advent been applied to experimental data within various research fields such as fluid mechanics, power systems, and thermal dynamics of buildings, to name a few. Its connection to spectral analysis of the Koopman operator was pointed out early, and some versions of DMD have been called Koopman Mode Decomposition (KMD), an acronym used from now on to refer to both. The performance of the algorithms is dependent on the spatial dimension, i.e. number of measurement locations, and the number of temporal data snapshots. In this presentation we discuss three KMD algorithms, and numerically assess their performance for application to two types of experimental data with varying temporal length (number of snapshots) and spatial dimension. In particular, it is shown that the newly proposed, so-called vector Prony analysis, performs well for data with low spatial dimension, in contrast to standard DMD.

Fredrik Raak
Kyoto University
f-raak@dove.kuee.kyoto-u.ac.jp

Yoshihiko Susuki
Kyoto University, JST
susuki@eis.osakafu-u.ac.jp

Igor Mezic
University of California, Santa Barbara
mezic@engineering.ucsb.edu

Takashi Hikihara
Department of Electrical Engineering
Kyoto University
hikihara.takashi.2n@kyoto-u.ac.jp

MS120

Extended Dynamic Mode Decomposition for Systems with Complex Dynamics

Extended Dynamic Mode Decomposition (EDMD) is a method for approximating the Koopman operator directly from data sampled from a dynamical system. It has proven successful for modeling some nonlinear systems with simple dynamics (e.g., fixed points and limit cycles), but has not been validated for use on complicated systems like turbulent fluid flows. In this work, we study the performance of EDMD on model problems with more complex dynamics (e.g., ergodic, mixing, chaotic). For ergodic systems with pure point spectrum, EDMD successfully finds the eigenvalues and eigenfunctions, and for mixing systems with no eigenfunctions, EDMD correctly predicts that there are no eigenvalues other than 1, but does not identify the continuous spectrum. For systems with both a structured component (e.g., point spectrum) and a random component (e.g., continuous spectrum), the method correctly separates the structured and random components.

Clarence Rowley
Princeton University
Department of Mechanical and Aerospace Engineering
cwrowley@princeton.edu

Vivian Steyert
Princeton University
vsteyert@princeton.edu

MS121

Efficient Locomotive Gaits for Swimming in Perfect Fluids

The literature on oscillatory fishlike swimming focuses overwhelmingly on sinusoidal pitching or heaving gaits, or a combination thereof. Perhaps this is because the forward swimming of many marine animals, such as thunniform swimmers, is most often attributable to purely sinusoidal kinematics. However, engineered systems need not mimic biological organisms, and it is natural to ask if non-sinusoidal gaits may perform better in some respects, for example as measured by thrust or propulsive efficiency. Indeed, recent experiments have achieved performance gains through the use of kinematics encoded by Jacobi-elliptic functions, and also by utilizing multifrequency modes. This work uses an unsteady boundary-element method to numerically explore periodic—but not purely sinusoidal—gaits of hydrofoils of practical engineering interest and swimming in a perfect fluid. We numerically confirm the qualitative features of the experimental studies, and we also identify optimal gaits and wake structures in several cases. It is shown that the best kinematic profile may be asymmetric. Finally, we remark on the relation of this work to the classical geometric-phase picture of locomotion in a principal bundle, and we allude to some of the challenges in practically extending this geometric view to systems which discretely shed vorticity.

Michael J. Fairchild
Department of Mechanical and Aerospace Engineering
Princeton University
mjf5@princeton.edu

Clarence Rowley
Princeton University
Department of Mechanical and Aerospace Engineering
cwrowley@princeton.edu

MS121

The Geometry of Self-Propulsion in (and on) Frictional Fluids

Certain animals and robots contend with flowable terrestrial environments like sand. We have developed a granular resistive force theory (RFT) that accurately describes locomotion in dry granular media (Zhang & Goldman, PoF, 2014) in the frictional fluid regime; however, this theory gives limited insight into the *character* of locomotion. Geometric mechanics (e.g. work of Shapere, Wilczek, Marsden, Kelly, etc) is a powerful framework relating position and orientation changes of a body to internal shape changes. Advances by Hatton and Choset (Eur. Phys. J. 2015) now enable application to large self-deformations; in collaboration we demonstrated the power of the combination of geometric mechanics and RFT through study of a three-link robot (two active, controllable DoF) swimming in granular media (Hatton et al, PRL, 2013). I will present our continued collaborative work extending these tools to describe the locomotion of animals and robots with more than two DoF. I will show that the cyclic self-deformations of sandfish lizards, shovel nosed snakes, sidewinder rattlesnakes, salamanders and mudskipper fish (and corresponding robophysical models) that make continuous or intermittent contacts with granular substrates can be represented as a linear combination of two shape basis functions — the shape configuration space can be described with two variables. With these approximations we gain insight into optimal self-deformation of high-DoF locomotors in granular media.

Daniel Goldman
Georgia Tech
School of Physics
daniel.goldman@physics.gatech.edu

MS121

3D Locomotion and Efficiency of a Yaw-Pitch Three-Link Robot in a Low Reynolds-Number Fluid

The efficiency and maneuverability of mircoorganisms provide an enticing model for the design of biomimetic robots. These observations serve as guides for the mechanical design and control of microswimmers, wherein changes in the internally-controlled degrees of freedom result in changes in net position and orientation of different robot designs. This work develops a novel geometric model of a non-planar three-link swimmer that executes three-dimensional maneuvers in a low Reynolds-number fluid. Whereas prior work on geometric swimming has considered mechanical designs that allow only planar motion, the model considered in this work allows for out-of-plane motions using yaw and pitch control of two internal joints. We leverage tools from geometric mechanics to derive a mapping from the underlying shape manifold to the swimmer's local velocities and analyze it's locomotion using this mapping. We present initial results that synthesize motion primitives for the swimmer, which make it move along canonical directions relative to an inertial frame. Concatenating motion primitives can serve as a convenient approach for robot motion planning because primitives are precomputed offline and do not require online re-computation or solving a trajectory optimization problem, every time a new target position is specified.

Jaskaran S. Grover, Tony Dear
Robotics Institute
Carnegie Mellon University
jaskarag@andrew.cmu.edu, tonydear@cmu.edu

Matthew Travers
Carnegie Mellon University
botics11@gmail.com

Howie Choset
Robotics Institute
Carnegie Mellon University
choset@cmu.edu

Scott D. Kelly
Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte
scott@kellyfish.net

MS121

Entrainment and Cooperative Locomotion in Nonholonomic Systems and Swimming Systems

The dynamics of a solid body moving through a fluid can be altered substantially by the presence of another body nearby. Under some circumstances, self-propelling bodies in proximity to one another can realize collective gains in efficiency as a result of their interactions. This phenomenon is well documented in the context of birds flying in formation to reduce drag resulting from vortex shedding, and more complex wake-body interactions play a role in determining the propulsive efficiency of schools of fishlike swimmers, but even irrotational flows provide the means for aggregated bodies to influence one another through added-mass effects. Wheeled robots can influence one another in similar ways when they operate atop a common platform that exhibits sufficient compliance to transmit vibrational energy from one robot to another, leading to variations of the kind of synchronization observed among pendulum clocks sharing such a platform. This talk will describe nonlinear phenomena arising in the coupled dynamics of wheeled robots that exploit inertial effects to propel themselves and will develop the analogy between the coupled locomotion of such robots and the coupled locomotion of bodies deforming in fluids.

Scott D. Kelly
Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte
scott@kellyfish.net

MS122

Synchronization in Experiments with Coupled Mechanical Oscillators

Abstract Not Available At Time Of Publication.

Karen Blaha
University of New Mexico
kb4hk@virginia.edu

MS122

Chimeras, Cluster States, and Symmetries: Experiments on the Smallest Chimera

Abstract Not Available At Time Of Publication.

Joseph Hart
University of Maryland
jhart12@umd.edu

MS122

Algorithms and Experiments for the Approximate Balanced Coloring Problem

Abstract Not Available At Time Of Publication.

David Philips
Operation Research
United States Naval Academy, Annapolis, MD, USA
dphillip@usna.edu

MS122

Approximate Cluster Synchronization in Networks with Symmetries

Abstract Not Available At Time Of Publication.

Francesco Sorrentino
University of New Mexico
Department of Mechanical Engineering
fsorrent@unm.edu

MS123

Interpreting Huybers' Glacial Cycles Model As a Nonsmooth Dynamical System

One of the most interesting open questions in Paleoclimate science is the mid-Pleistocene Transition (MPT) problem, which surrounds the unknown cause that drove the change in the dominant period of deglaciation from 41 kyr to 100 kyr. Huybers' glacial cycles model was first suggested by Peter Huybers' and Carl Wunsch in 2005 to explain the glacial variability of the earth's climate, in hopes of shedding light on what prompted the sudden shift in the periodicity of the mid-Pleistocene. In this talk, I will present how to construct a nonsmooth dynamical system (in particular a Filippov system) from Huybers' model by creating a manifold from the quotient space inspired by the threshold of the model. Then I will discuss a way of reducing the system to a circle relation and possible implications of this approach. Through imposing well-studied structures on Huybers' model, we hope to gain further insight into

the mid-Pleistocene Transition problem.

Somyi Baek
University of Minnesota
somyib@umn.edu

MS123

Conceptual Climate Models with Global Feedback Mechanisms

In contrast to highly complex general circulation models of the Earths climate, conceptual climate models concern the behaviour of only a few variables. The goal is to obtain a model that is amenable to mathematical analysis, while still giving an adequate description of the phenomenon under consideration. The modeling of feedback mechanisms on a global scale is of particular relevance in this context. This talk will give a brief overview of different types of conceptual climate models and the dynamical systems tools available for their analysis.

Bernd Krauskopf
University of Auckland
Department of Mathematics
b.krauskopf@auckland.ac.nz

MS123

Understanding the Variability of the Indian Monsoons - Combining Data with Model

The Indian monsoons show significant year-to-year variability, as well as variability within a given rainfall season. It is unknown how much of this variability is driven by climatic conditions external to the Indian subcontinent, or internal feedback mechanisms. While many studies have shown correlations between global climate states and the Indian summer monsoon rainfall, the dynamical connections are not well understood. In our study, we develop a highly simplified box model of the monsoon system, driven by real boundary conditions derived from satellite data. Daily values of near-surface temperature, winds, and humidity measurements are used to compute heat and moisture fluxes into the box situated over India and Bangladesh. Precipitation is then computed from vertical air flux, evaporation of groundwater, and parameterized cloud formations. Processes within the box are modeled using standard physics currently employed in state-of-the-art climate models. The dynamical variables are heat, moisture, and groundwater content. We hope that this approach will give us some insight about the role and importance of internal feedbacks and external climate states on the monsoon rainfall.

Raj Saha
University of North Carolina
rajsaha@physics.unc.edu

MS124

Data-Driven Correction of Model Error for Forecasting

Semiparametric forecasting is introduced as a method of addressing model errors arising from unresolved physical phenomena. While traditional parametric models are able to learn high-dimensional systems from small data sets, their rigid parametric structure makes them vulnerable to model error. On the other hand, nonparametric models have a very flexible structure, but they suffer from the curse-of-dimensionality and are not practical for high-dimensional systems. The semiparametric approach loosens the structure of a parametric model by fitting a data-driven nonparametric model for the parameters. Given a parametric dynamical model and a noisy data set of historical observations, an adaptive Kalman filter is used to extract a time-series of the parameter values. A nonparametric forecasting model for the parameters is built by projecting the discrete shift map onto a data-driven basis of smooth functions. Ensemble forecasting algorithms extend naturally to the semiparametric model which can effectively compensate for model error, with forecasting skill approaching that of the perfect model. Semiparametric forecasting is a generalization of statistical semiparametric models to time-dependent distributions evolving under dynamical systems.

Tyrus Berry, John Harlim
Pennsylvania State University
tyrus.berry@gmail.com, jharlim@psu.edu

MS124

Uncertainty Quantification for Generalized Langevin Dynamics

We present efficient finite difference estimators for goal-oriented sensitivity indices with applications to the generalized Langevin equation (GLE). In particular, we apply these estimators to analyze an extended variable formulation of the GLE where other well known sensitivity analysis techniques such as the likelihood ratio method are not applicable to key parameters of interest. These easily implemented estimators are formed by coupling the nominal and perturbed dynamics appearing in the finite difference through a common driving noise, or common random path.

Eric J. Hall
University of Massachusetts
hall@math.umass.edu

Markos A. Katsoulakis
University of Massachusetts, Amherst
Dept of Mathematics and Statistics
markos@math.umass.edu

Luc Rey-Bellet
Department of Mathematics & Statistics
University of Massachusetts
luc@math.umass.edu

MS124

Accounting for Model Errors from Unresolved Scales by Stochastic Parametrization in Ensemble Kalman Filters

We investigate a discrete-time stochastic parametrization method to account for model errors due to unresolved scales in the context of the ensemble Kalman filter with perturbed observations. The parametrization quantifies the model errors and produces an improved non-Markovian forecast model, which generates high quality forecast ensembles and improves filter performance. We compare this method with the standard method of dealing with model errors through covariance inflation and localization, and illustrate the comparison with numerical simulations on the two-layer Lorenz 96 system. Results show that when the ensemble size is sufficient, the parametrization is more effective in accounting for such model errors than inflation and localization; if the ensemble size is small, inflation and

localization are needed, but the parametrization provides a further improvement in performance. The general implications of the results is discussed.

Fei Lu
Department of Mathematics, UC Berkeley
Mathematics group, Lawrence Berkeley National Laboratory
flu@lbl.gov

Alexandre Chorin
Department of Mathematics
University of California at Berkeley
chorin@math.berkeley.edu

Xuemin Tu
University of Kansas
xuemin@ku.edu

MS124

Estimating Parameters with Linear Response Statistics

I will present a new parameter estimation method for Itô diffusions such that the resulting model predicts the equilibrium statistics as well as the sensitivities of the underlying system to external disturbances. Our formulation does not require the knowledge of the underlying system, however we assume that the linear response statistics can be computed via the fluctuation-dissipation theory. In this talk, I will demonstrate the consistency of our method on a Langevin dynamics.

John Harlim
Pennsylvania State University
jharlim@psu.edu

Xiantao Li
Department of Mathematics
Pennsylvania State University
xli@math.psu.edu

He Zhang
Department of Mathematics
The Pennsylvania State University
hqz5159@psu.edu

MS125

Stochastic Dynamics that are Central to Biological Mechanisms: Sleep-wake Transitions

The study of sleep-wake transitions is an excellent arena for the methods of stochastic analysis. Sleep and the transitions between sleep and wake are variable within each individual and the frequency of transitions and the length of bouts change across the lifespan. In addition, there is enormous variability between individuals. Sleep-wake transitions and the lengths of bouts are easy to measure, however, they depend on underlying neural stochastic mechanisms that are not well understood. In this talk, we will describe various approaches for analytical, statistical and numerical calculations about the nature of sleep-wake transitions and the underlying biological mechanisms.

Janet Best
The Ohio State University
Department of Mathematics
jbest@math.ohio-state.edu

MS125

Yeast Cultures Have Large Coupling Strengths: Random Perturbations on Cell-cell Coupling Dynamics

We study the effects of random perturbations on collective dynamics of a large ensemble of interacting cells in a model of the cell division cycle. We consider a parameter region for which the unperturbed model possesses asymptotically stable two-cluster periodic solutions. Two biologically motivated sources of noise are introduced into the cell cycle system and we compare them with the model that has Gaussian white noise perturbations. In simulations, we explore how an ordered two-cluster periodic state of cells becomes disordered by the increase of noise and a uniform distribution emerges for large noise. As a corollary to the results, we can estimate the coupling strength of the cell cycle in yeast autonomous oscillation experiments where clustering is observed. This work was done with Alexander Neiman and Todd Young at Ohio University.

Xue Gong
Department of Mathematics and Computer Science
Augustana College
xuegong@augustana.edu

Gregory Moses
Ohio University
gm192206@ohio.edu

Alexander Neiman
Ohio University
Department of Physics and Astronomy
neimana@ohio.edu

Todd Young
Ohio University
Department of Mathematics
youngt@ohio.edu

MS125

Hope Bifurcation in Random Dynamical Systems

Despite the obvious relevance to applications, a bifurcation theory for random dynamical systems is still only in it's infancy. We discuss some progress on the understanding of the dynamics of a random dynamical systems near a (deterministic) Hopf bifurcation that illustrate recent advances and remaining challenges. This presentation is based on joint work with Maximilian Engel (Imperial College London), Martin Rasmussen (Imperial College London) and Doan Thai Son (Hokaido University).

Jeroen Lamb
Department of Mathematics
Imperial College London
jswlamb@gmail.com

MS125

Transitions in a Genetic Transcriptional Regulatory System Under Lévy Motion

Based on the stochastic differential equation model of a single genetic regulatory system, we examine the dynamical effects of noisy fluctuations from the synthesis reaction, on the evolution of the transcription factor activator in terms of its concentration. The fluctuations can be modeled by Brownian motion and a pure jump Lévy motion, respectively. Two deterministic quantities, the mean first exit time (MFET) and the first escape probability (FEP), are used to investigate the transition from the low to high concentration states.

Yayun Zheng
School of Mathematics and Statistics,
Huazhong University of Science and Technology
yayun2046@163.com

MS126

The Dynamics of Interacting Pulses in an Extended Klausmeier Model

The extended Klausmeier, or Klausmeier-Gray-Scott, equation models the ecosystem dynamics of vegetation patterns in semi-arid regions. The equation is especially used to study the desertification process, i.e. the process through which a homogeneously vegetated terrain eventually may degenerate into bare soil (under changing climatological circumstances). In the model, decreasing yearly rainfall first initiates the formation of (Turing) patterns that evolve into localized vegetation patches surrounded by bare soil – patterns that are observed throughout the globe. The next stage of the desertification process is governed by the semi-strong interaction of these (far-from-equilibrium) vegetation patches – that have the character of homoclinic pulses in one spatial dimension. In this terminology – and the the 1D setting – desertification is caused by the interaction and mutual annihilation of pulses (and the (re-)emergence of pulses if the external circumstances improve). A central topic of this talk will be the question whether the desertification process has a catastrophic or a more regular nature. It will be argued that this is strongly related to the (ir)regularity of the multi-pulse pattern.

Arjen Doelman
Mathematisch Instituut
doelman@math.leidenuniv.nl

Robbin Bastiaansen
Mathematical Institute
Leiden University
r.bastiaansen@math.leidenuniv.nl

MS126

Interactions of Spatially Localized Structures in Bioconvection of Photosensitive Microorganism

Euglena gracilis is a unicellular flagellated photosynthetic alga. The suspension of *Euglena* has behavioral responses to light environment, and macroscopic localized bioconvection patterns are generated when illuminated from below. One of the fundamental structures is bioconvection unit, a pair of convection cells sandwiching a high cell density region [”Localized Bioconvection Patterns and Their Initial State Dependency in Euglena gracilis Suspensions in an Annular Container”, E. Shoji, et al. J. Phys. Soc. Jpn. 83, 043001 (2014)]. Experimental studies show various types of interaction in the localized convection cells; a quasi-steady bound states and collisions are typical examples. After summarizing individual behavior, we show numerical simulations of the interactions based on a hydrodynamic model proposed by one of the authors, which is based on of the experimental measurements and dilute assumptions. Stability of equally-placed bioconvection units will be discussed.

Makoto Iima, Takayuki Yamaguchi
Hiroshima University
makoto@mis.hiroshima-u.ac.jp, ymtk@hiroshima-u.ac.jp

MS126

Dynamics of Localized Structures in Dissipative Systems

We highlight several key features of structures and dynamics of spatially localized patterns arising in dissipative systems. The model systems include chemical reactions, fluid mechanics, nonlinear optics, gas discharge, plant ecology and adaptive behaviors of amoeba. These patterns are much simpler than single living cell, however they seem to inherit several characteristic living-state features, Despite the diversity, there are common mathematical structures and driving mechanisms leading to rich structures and their associated dynamics including snaking bifurcation, self-replication, self-excitation, and collision dynamics. The interplay between intrinsic and extrinsic instabilities is a key to understand those dynamics and one of the powerful approach is to clarify the global geometric interrelation among all relevant solution branches with approximate unfolding parameters. We present several illustrative examples to show the effectiveness of such geometric approach as well as classical singular perturbation methods.

Yasumasa Nishiura
WPI-AIMR, Tohoku University
Japan
yasumasa@pp.iij4u.or.jp

MS126

Dynamics of Traveling Spots with Oscillatory Tails in Heterogeneous Media

Interactions between traveling spots with oscillatory tails and heterogeneities for a generalized three-component FitzHugh-Nagumo equations are investigated in two-dimensional space. We in particular focus on the case that heterogeneity is given in the form of disk shape. Various types of heterogeneity-induced ordered patterns (HIOPs) appeared. The important aspect of these localized patterns is that both of them have oscillatory tails and they interact through their tails when a traveling spot approaches to an HIOP. As a result, the interaction manner of them is very different from that of non-oscillatory case. At the first step we address the global bifurcation structure of HIOPs because many different stable HIOPs coexist at the same parameter. At the second step collisions between traveling spot and HIOP are investigated. Finally four-dimensional reduced ODEs is derived and mathematical structure of the interactions are elucidated.

Takeshi Watanabe
School of Engineering, The University of Tokyo
watanabe@rocketlab.t.u-tokyo.ac.jp

Yasumasa Nishiura
WPI-AIMR, Tohoku University
Japan
yasumasa@pp.iij4u.or.jp

MS127

Coupling Single Neuronal Activity to Complex

Brain Functions: Large-Scale, High-Resolution Approaches to Dissect and to Modify Neuronal Network Activities

In order to understand how behavioral and network level functions emerge from the cooperation of neuronal populations, a representative fraction of neurons must be simultaneously monitored at the single-cell level. We developed large-scale electrophysiological recording methods with precise manipulation approaches, which can give birth to on demand, closed-loop therapeutic interventions for many drug resistant neuropsychiatric disorders. I will introduce our recent results we gained to understand the development of hypersynchronous events in the hippocampus. Our translational efforts employing closed-loop transcranial electrical stimulation on human patients to establish an acute intervention approach that promptly disrupt pathologic network oscillations will be also highlighted in my talk.

Antal Berenyi
University of Szeged
drberenyi@gmail.com

MS127

Control, Optimization and the Dynamics of Function in Neuronal Networks

This talk will explore how the control properties of neuronal networks, mediated by their dynamics, may confer functional advantages in terms of information processing capacity. Analytical frameworks for linking control properties and function at two spatial scales will be highlighted. Examined first will be the issue of how the dynamics of early sensory networks determine their sensitivity to stimulus orientation and novelty, towards enabling improved decoding of stimulus identity. This analysis allows for predictions regarding the neural responses elicited by different stimulus types, under the premise that such responses are optimal for control-theoretic decoding functions. Evidence of the predicted responses in the olfactory system will be shown. The concept of optimality will then be further explored in the context of information processing objectives at broader spatial scales. Analysis will be presented that shows how brain regions interacting via local, optimal rules may give rise to predictable, yet nontrivial attractor landscapes at the large-network level. Evidence of such attractors, or microstates, will be presented from large scale recordings of human neural activity in resting awake and pharmacologically unconscious conditions. The alteration to the attractor structure, and thereby the network control properties, in the unconscious condition will be especially highlighted.

ShiNung Ching
Washington University in St. Louis
shinung@ese.wustl.edu

MS127

Fragility in the Human Decision Making System: When Irrationality Hijacks Logic

Decision-making (DM) links cognition to behavior and is a key driver of personality, fundamental for survival, and essential for our ability to learn and adapt. Humans make logical decisions (e.g. maximize expected reward), but this rationality is influenced by internal biases such as emotions. Psychiatric patients who have dysfunctional cognitive and emotional circuitry frequently make irrational decisions. Unfortunately, the function of relevant neural circuits in humans is uncharted at fine temporal scales, limiting the understanding of changes underlying disruption associated with diseases. In this study, we localize neural circuits critically involved in human DM on a millisecond scale. Ten subjects, implanted with depth electrodes for clinical purposes, performed a gambling task while we recorded local field potential activity from deep and peripheral brain structures. The gambling task consisted of logic-driven trials and trials that were ambiguous - decisions likely were based on internal biases. We first construct dynamical models of betting behavior for each subject that allows both logic and biases to integrate in DM. The models capture variability amongst subjects ranging from irrational to logical. Analysis of the neural data suggests key structures (e.g. cuneus, amygdala, orbitofrontal cortex) encode different components of the DM system such as risk of reward and provides new insight into how humans link their internal biases with logic to make decisions.

Sridevi V. Sarma, Pierre Sacre
Johns Hopkins University
sree@jhu.edu, pierre.sacre@gmail.com

John Gale
Emory University
john.t.gale@emory.edu

Jorge Martinez-Gonzalez
Cleveland Clinic
jalmartinez@sbcglobal.net

MS127

Moving to the Network Level in Brain Activity Control: Implications for Cognition and Development

While the successful control of brain dynamics remains a great challenge, new advancements in both neural technologies and relevant theories make it an opportune moment to revisit this topic. We review key developments in the control of single or a few neurons, as well as in specific domains such as Parkinsons disease. These successes naturally bring to light limitations and key questions in the field, suggesting potential areas for growth and work. We discuss efforts to study the brain from a systems level, which utilize developments in the field of connectomics and in network control theory. Linear control theory links brain regions to their canonically identified cognitive tasks, while connecting to individual differences in cognitive performance, as well as brain development in the maturation of a child into adulthood.

Evelyn Tang
University of Pennsylvania
evelynt@seas.upenn.edu

MS128

The Motion of Objects Floating on the Ocean Surface

We propose a new Maxey–Riley set for the motion of spheres floating at the ocean–atmosphere interface. The new set predicts long-term accumulation in the center of the subtropical gyres. Observed distributions of undrogued drifters and plastic debris support the prediction.

Francisco J. Beron-Vera
RSMAS, University of Miami

fberon@rsmas.miami.edu

M. Josefina Olascoaga
University of Miami
jolascoaga@rsmas.miami.edu

Rick Lumpkin
NOAA, AOML
rick.lumpkin@noaa.gov

MS128

A Comparison of Lagrangian Methods for Coherent Structure Detection

Coherent Lagrangian (i.e., material) structures are ubiquitous in unsteady fluid flows, often observable indirectly from tracer patterns they create, e.g., in the atmosphere and the ocean. Despite these observations, a direct identification of these structures from the flow velocity field (without reliance on seeding passive tracers) has remained a challenge. Several heuristic and mathematical detection methods have been developed over the years, each promising to extract materially coherent domains of arbitrary unsteady velocity fields over a finite time interval of interest. Here we review a number of these methods and compare their performance systematically on three benchmark velocity data sets. Based on this comparison, we discuss the strengths and weaknesses of each method, and recommend minimal self-consistency requirements that Lagrangian coherence detection tools should satisfy.

Alireza Hadjighasem
McGill University
alirezah@mit.edu

Mohammad Farazmand
School of Physics
Georgia Institute of Technology
mfaraz@mit.edu

Daniel Blazevski
Insight Data Science
daniel.blazevski@gmail.com

Gary Froyland
UNSW Australia
g.froyland@unsw.edu.au

George Haller
ETH, Zurich, Switzerland
georgehaller@ethz.ch

MS128

Mathematical Relations Between Geometric and Probabilistic Coherent Structure Detection Methods

In this talk, we first review three prominent objective detection methods for coherent Lagrangian vortices. These are—in chronological order—the probabilistic transfer operator approach developed by Froyland and co-workers, the geodesic approach developed by Haller and co-workers, and recent Laplace operator-based approaches developed by Froyland as well as by the authors. We present either theorems or strong numerical evidence for close mathematical connections between these methods.

Daniel Karrasch
Technische Universität München, Germany
karrasch@ma.tum.de

Johannes Keller
TU Munich
keller@ma.tum.de

MS128

Objective Eulerian Coherent Structures

We present a variational theory of Objective Eulerian Coherent Structure (OECS) in two-dimensional nonautonomous dynamical systems (*Serra, M. and Haller, G., Chaos 26(5), 2016*). OECSs uncover the instantaneous skeleton of the overall dynamical system, acting as theoretical centerpieces of short-time trajectory patterns. OECSs are computable at any time instant without any assumption on time scales, and hence are promising tools for flow-control and real-time decision-making problems. We also show that OECSs are null-geodesics of appropriate Lorentzian metrics. Exploiting the geometry of geodesic flows, we derive a fully automated procedure for the computation of OECSs (*Serra, M. and Haller, G., Proc. of the Royal Soc. A (2017) 473 20160807*). As an illustration, we apply our results to ocean velocity data.

Mattia Serra
ETH Zurich, Switzerland
serram@ethz.ch

George Haller
ETH, Zurich, Switzerland
georgehaller@ethz.ch

MS129

A Dynamical Systems Approach to the Pleistocene Climate - Part II of II

In this presentation, we continue the analysis of the Pleistocene climate model proposed by Maasch and Saltzman, extending the results obtained for the liming case ($q = \infty$) discussed in the previous presentation to the case of finite q. For $q \gg 1$, the Maasch-Saltzman model is a fastslow system. We show that there exists a family of invariant slow manifolds, so the long-term dynamics are essentially two-dimensional. For the general case $q > 1$, we show that there exists a critical value q_c such that the long-term dynamics evolve on a two-dimensional center manifold, while for $1 < q < q_c$ the dynamics are truly three-dimensional.

Hans Engler
Georgetown University
engler@georgetown.edu

Hans G. Kaper
Georgetown University
Argonne National Laboratory
kaper@mcs.anl.gov

Tasso J. Kaper
Boston University
Department of Mathematics
tasso@math.bu.edu

Theodore Vo
Boston University

theovo@math.bu.edu

MS129

A Dynamical Systems Approach to the Pleistocene Climate - Part I of II

In 1990, K. Maasch and B. Saltzman introduced a three-dimensional dynamical system to explain the glacial cycles of the Pleistocene Epoch. The model consists of three ODEs with four parameters, and emphasizes the role of atmospheric CO_2 in the generation and persistence of periodic orbits (limit cycles). In this presentation, we review the physics underlying the Maasch-Saltzman model and focus on a limiting case, obtained by letting one of the parameters (q, a ratio of two characteristic times) tend to infinity. The resulting two-dimensional model has many of the same dynamical features as the full Maasch-Saltzman model. In the special case of $\mathbf{Z}_2$ symmetry, a Bogdanov–Takens (BT) point serves as an organizing center for the local and global dynamics. In the absence of symmetry, the BT point splits into two BT points, with different local dynamics in their neighborhoods.

Hans Engler
Georgetown University
engler@georgetown.edu

Hans G. Kaper
Georgetown University
Argonne National Laboratory
kaper@mcs.anl.gov

Tasso J. Kaper
Boston University
Department of Mathematics
tasso@math.bu.edu

Theodore Vo
Boston University
theovo@bu.edu

MS129

Palaeoclimate Dynamics Modelled with Delay Differential Equations

The Quaternary period is characterised by oscillations between glacial and interglacial states along with unexplained jumps in temperature on shorter timescales (Dansgaard-Oeschgar events). External orbital forcing only explains some of the behaviour in the climate record, so it is necessary to study the associated internal processes of the climate variables involved. We study where delays can play a role in these internal processes. Delayed feedback mechanisms are typically described by delay differential equations (DDEs), i.e. differential equations which depend on past states of the system. These can be useful in parameterising small-scale processes into just an effective delay of the feedback. In climate models, delays can approximate the transport of mass or energy across large distances. We explore possible delays in the climate system relative to the timescales of the Quaternary period. In particular we focus on delays related to deep ocean transport in the Atlantic. A few different conceptual climate DDE models are studied, and their behaviour is compared to the climate record.

Courtney Quinn
University of Exeter
c.quinn2@exeter.ac.uk

MS129

Interconnected Climate Variability in the Pacific and Indian Oceans

The Pacific Ocean is home to one of the dominant large-scale climate modes arising from a coupled instability of the ocean/atmosphere system: the El Niño-Southern Oscillation (ENSO). ENSO events occur irregular on interannual timescales and are characterized by large amplitude changes of Sea Surface Temperatures (SSTs) in the Central and Eastern equatorial Pacific. These SST changes induce large shifts of the atmospheric circulation, thereby causing anomalous droughts and flooding events in many regions of the Earth. While linear ENSO theory has matured over recent decades, many aspects of ENSOs complexity are still puzzling. These include for instance ENSOs temporal evolution irregularity, its spatial complexity, and its distinct nonlinear climate impacts (such as precipitation), which depend crucially both on the ENSO phase (El Niño or La Niña) and the annual cycle phase. The Indian Ocean and the Atlantic exhibit similar modes of intrinsic climate variability, albeit considerably smaller both in spatial scale and amplitude. One of these climate modes is the Indian Ocean Dipole (IOD). Here we are presenting a simple conceptual model framework that captures the observed interactions between ENSO and the IOD. Using this model we are able to explain a variety of spectral and cross-correlation characteristics in observable climate variables, with important implications for the interpretation of seasonally modulated climate variability.

Malte Stuecker
University of Hawaii at Manoa
stuecker@soest.hawaii.edu

MS130

Chaotic Ollations of Smple Mchanical Sstems

We describe two simple experimental systems with Lorenz like chaotic dynamics: a MalkusLorenz water wheel and an electromechanical chaotic oscillator. The MalkusLorenz water wheel dynamics are found to be in good, but not perfect, agreement with predictions from the Lorenz model. We address the issue of multi-parameter estimation from scalar outputs of this chaotic system. The electromechanical oscillator produces chaotic oscillations with a topological structure similar the Lorenz butterfly or Rsslers folded-band oscillator, depending on the configuration. An interesting feature of this oscillator is that its model admits an exact analytic solution.

Lucas Illing
Reed College
illing@reed.edu

MS130

Coins Falling in Water

Objects falling freely under gravity through a fluid medium may follow various periodic or chaotic paths depending on their geometry, the ratio of the disc to fluid density, and the fluid viscosity. Understanding the origin and nature of these nonstraight paths is relevant to many branches of science and engineering. Examples range from seed dispersal and gliding animals to unpowered robotic vehicles. In this talk, we present a series of experimental studies of the falling modes of coins of various shapes and how these falling modes influence the probability distribution of the coins landing sites.

Lionel Vincent
Aerospace and Mech. Engineering
University of Southern California
l.vincent@usc.edu

Try Lam
NASA Jet Propulsion Laboratory
try.lam@jpl.nasa.gov

Eva Kanso
University of Southern California
kanso@usc.edu

MS130

Pattern Formation of Swarms of Artemia Franciscana

Swarming is a ubiquitous self-organization phenomenon which occurs in many biological systems such as groups of the flocking of birds and insects, the schooling of fish, and the collection of bacteria. This sort of behavior is an emergent phenomenon as most of this behavior arising without any sort of centralized control or leadership. Swarming depends primarily on local interactions between individuals in the swarm. We will discuss the patterns that can be observed by the swarming of brine shrimp, specifically the Great Salt Lake strain of Artemia franciscana, at high concentration. These patterns can be easily observed with simple tabletop experiments; however, the cause of these patterns are unknown. We experimentally test the effects on certain physical parameters such as concentration, temperature, salinity, luminosity and the relationship of extended-area to depth on the patterns that arise. We then develop a model for the shrimps behavior which will also yield the same sort of patterns. We hope to model the basic length and times scales of the patterns, the patterns selected, the stability of those patterns, and the transitions that occur between patterns.

Andrea J. Welsh, Krishma Singal, Flavio H. Fenton
Georgia Institute of Technology
awelsh8@gatech.edu, ksingal3@gatech.edu, flavio.fenton@physics.gatech.edu

MS131

Deterministic and Stochastic Stability of Arabidopsis Flowering Model

Experimental studies of the flowering of Arabidopsis Thaliana have shown that a large complex gene regulatory network is responsible for its regulation. In this work, we consider a deterministic and stochastic delayed non-linear dynamic model of Arabidopsis flowering time based on the deterministic model introduced in Valentim et al 2015. We investigate the conditions for deterministic and stochastic stability of the full model. By using a quasi-steady state approximation, the system is reduced by focusing on a subnetwork composed of the transcription factor Suppressor of Overexpression of Constants 1 (SOC1) and two important floral meristem identity genes, Leafy (LFY) and Apetala1 (AP1). We also consider three motifs from the reduced network, based on LFY and AP1, which lead to simplified models of the GRN. The steady state regimes and the effect of stochasticity are investigated analytically and numerically for the full and reduced models. The results contribute to the better understanding of the role of LFY and AP1 in the flowering of Arabidopsis thaliana.

Maia Angelova
Department of Mathematics and Information Sciences
Northumbria University
maia.angelova@northumbria.ac.uk

Emrah Haspolat
Deaprtment of Mathematics, Physics and Electrical Engineerin
Northumbria University
emrah.haspolat@northumbria.ac.uk

Benoit Huard
Northumbria University
Department of Mathematics, Physics & Electrical Engineering
benoit.huard@northumbria.ac.uk

MS131

Delays and Nonlinearities in Biological Clocks

As an introduction to this mini-symposium on gene regulatory networks we provide a brief history of models for cellular oscillators, beginning with the three-variable Goodwin oscillator with negative feedback. We then consider a very general model for a cyclic sequence of J reactions, where reacting species j is the source for the generation of species $j+1$, until the very last species J, which provides negative feedback to the first species $j = 1$. These species may represent, for example, the concentration of mRNA, which is translated into a sequence of proteins, and a final product that acts to inhibit the transcription of mRNA. From our analysis we are able to generalize and expand on results obtained from a variety of simpler models. For example, we show that rather than the details of specific reaction steps, it is the net nonlinearity and the net delay of the system that determine the onset and properties of oscillatory solutions due to a Hopf bifurcation. Or, a linear sequence of reactions with non-uniform coefficients can be captured by an appropriately chosen distributed delay, hence, generalizing what is often referred to as the linear-chain trick.

Thomas W. Carr
Southern Methodist University
Department of Mathematics
tcarr@smu.edu

MS131

Characterization of Transcriptional Delays under Time-Varying Temperatures

Delays play a critical role in genetic networks through their nonlinear effects on cell signaling. For example, it is often delays that allow for oscillations in a genetic network given its narrow parameter range. One of the most prevalent environmental factors that affect timing and regulation of gene expression is temperature. However, it is not known how delays change with time-varying temperatures. We analytically derive the time dependence of delay distributions in response to time-varying temperature changes. We find that the resulting time-varying delay is nonlinearly dependent on parameters of the time-varying temperature such as amplitude and frequency; therefore, applying an Arrhenius scaling may result in erroneous conclusions. We apply the results to a model of a synthetic gene oscillator with dynamics described by a delay differential equation. This model describes a genetic oscillator that maintains

the same period of oscillation for a wide range of temperatures. We show that entrainment of the synthetic gene oscillator follows from the same mechanism that results in temperature compensation.

Marcella M. Gomez
Department of Electrical Engineering and Computer Science
University of California, Berkeley
mmgomez@berkeley.edu

Richard Murray
Caltech
Control and Dynamical Systems
murray@cds.caltech.edu

Matthew Bennett
Rice University
matthew.bennett@rice.edu

MS131
Which Delays Matter in Gene Expression?

Many gene expression models either include separate transcription and translation delays, or simply a total (transcription + translation) expression delay for each protein. However, some models also include delays representing promoter and ribosome binding site (RBS) clearance. Do these clearance delays matter? Intuitively, one would think that delays of a few seconds matter little when the total gene expression time is of the order of one minute (prokaryotes) to several minutes or longer (eukaryotes). On the other hand, including a delay for promoter clearance, for example, guarantees a minimum temporal spacing between transcription initiation events. Are there observable consequences associated with promoter clearance, or with the analogous process of RBS clearance, in delay-differential equation models of gene expression? Do these clearance times affect the statistics of protein expression bursts in delay-stochastic models? And does it matter if we represent these processes with a fixed delay, or is a distributed delay necessary? These questions will be explored in the context of a simple model for the expression of a single, constitutively expressed gene.

Marc R. Roussel
University of Lethbridge, Canada
Department of Chemistry and Biochemistry
roussel@uleth.ca

MS132
Localized Structures in Nonlinear Optical Resonators

We analyze the dynamics and stability of localized structures in the mean-field Lugiato-Lefever equation describing driven nonlinear optical resonators. We show how different types of localized structures can form depending on system parameters, such as pump power, cavity detuning, and the regime of chromatic dispersion (normal vs. anomalous). We discuss that these structures are organized in so-called homoclinic or collapsed snaking diagrams, and that they can undergo a variety of dynamical instabilities, such as oscillatory and chaotic dynamics [Phys. Rev. A **5**4, 5707 (1996), Opt. Expr. **2**1, 9180 (2013), Phys. Rev. A **8**9, 043813 (2014), Phys. Rev. A **8**9, 063814 (2014), Opt. Expr. **2**3, 7713 (2015), Phys. Rev. A **9**3, 063839 (2016), Opt. Lett. **4**1, 2402 (2016)]. These results are timely as localized light pulses in the Lugiato-Lefever equation have been shown to adequately describe optical Kerr frequency combs. Frequency combs are widely studied as they can be used to measure light frequencies and time intervals with great accuracy in a compact integrated platform [Science **3**32, 555 (2011), Phys. Rev. Lett. **1**07, 063901 (2011), Nat. Photon. **6**, 480 (2012)]. As such, our work provides new insights into the generation and stability of these frequency combs.

Lendert Gelens
KU Leuven, Belgium
lendert.gelens@kuleuven.be

Pedro Parra-Rivas
Applied Physics Research Group
Vrije Universiteit Brussel, Belgium
parrariv@gmail.com

Damia Gomila
IFISC (CSIC-UIB)
Instituto de Fisica Interdisciplinar y Sistemas Complejos
damia@ifisc.uib.es

François Leo
OPERA-Photonique, Université libre de Bruxelles (ULB)
50 av. F.D. Roosevelt, CP194/5, B-1050 Bruxelles, Belgium
francleo@ulb.ac.be

Stéphane Coen
Department of Physics, University of Auckland, New Zealand
s.coen@auckland.ac.nz

Edgar Knobloch
University of California, Berkeley -
Nonlinearity, Institute of Physics
knobloch@berkeley.edu

MS132
Patterns vs. Localized Structures

We analyze the formation of patterns and localized structures in the Lugiato-Lefever equation. For some parameter regions this model presents a subcritical Turing instability leading to the formation of periodic patters and localized structures displaying homoclinic snaking. In this regime localized solutions have clearly different properties than the patterns. For other parameter values, however, the system goes through a Quadruple Zero (QZ) point where the critical wavenumber of the pattern forming instability goes to zero. In this case we show how patterns and localized states are no longer that different. In fact, the bifurcation diagram of localized states changes dramatically going through that point, resembling more the typical bifurcation structure of periodic patterns. We will also discuss the role of the interaction between localized structure in this scenario.

Damia Gomila
IFISC (CSIC-UIB)
Instituto de Fisica Interdisciplinar y Sistemas Complejos
damia@ifisc.uib.es

Pedro Parra-Rivas
Applied Physics Research Group
Vrije Universiteit Brussel, Belgium
parrariv@gmail.com

Lendert Gelens
KU Leuven, Belgium
lendert.gelens@kuleuven.be

Edgar Knobloch
University of California at Berkeley
Dept of Physics
knobloch@berkeley.edu

MS132

Forced Snaking

We study spatial localization in the real subcritical Ginzburg-Landau equation

$$u_t = m_0 u + m_1 \cos\left(\frac{2\pi}{\ell}x\right) u + u_{xx} + d|u|^2 u - |u|^4 u$$

with spatially periodic forcing. When $d > 0$ and $m_1 = 0$ this equation exhibits bistability between the trivial state $u = 0$ and a homogeneous nontrivial state $u = u_0$ with stationary localized structures which accumulate at the Maxwell point $m_0 = -3d^2/16$. When spatial forcing is included its wavelength is imprinted on u_0 creating conditions favorable to front pinning and hence spatial localization. We use numerical continuation to show that under appropriate conditions such forcing generates a sequence of localized states organized within a snakes-and-ladders structure centered on the Maxwell point, and refer to this phenomenon as *forced snaking*. We determine the stability properties of these states and show that longer lengthscale forcing leads to stationary trains consisting of a finite number of strongly localized, weakly interacting pulses exhibiting *foliated snaking*. [Ponedel, B. and Knobloch, E., Eur. Phys. J. Special Topics, 2016 (to be published).]

Benjamin C. Ponedel
Department of Physics, UC Berkeley
bponede1@berkeley.edu

Edgar Knobloch
University of California at Berkeley
Dept of Physics
knobloch@berkeley.edu

MS132

Spatially Localized Patterns in Networks of Spiking Neurons

We study spatially localized solutions in a neural field model that describes the macroscopic dynamics of quadratic integrate-and-fire neurons. These localized solutions are the physical representation of working memory and short-term memory. They bifurcate from a branch of stationary homogeneous solutions, in the proximity of a saddle-node bifurcation of the spatially clamped model. The solution branch exhibits damped snaking for homogeneous (translationally invariant) synaptic connections. If synaptic connections are heterogeneous (specifically, if they are sinusoidally modulated in space) then localized solution branches exhibit a typical snakes-and-ladders structure, previously reported by Avitabile and Schmidt for an Amari-type neural field model. In addition, we study the impact of external oscillatory forcing on these localized solutions, which represents oscillations that are ubiquitous in neuronal systems. The resulting spatiotemporal dynamics is organized by limit points and period doubling bifurcations, which can lead to the annihilation of localized patterns at different frequencies and amplitudes. This demonstrates the importance of the presence of oscillations in neuronal systems, and the role they play in information processing.

Helmut Schmidt
Centre de Recerca Matematica, Barcelona, Spain
hschmidt@crm.cat

Daniele Avitabile
School of Mathematical Sciences
University of Nottingham
Daniele.Avitabile@nottingham.ac.uk

Ernest Montbrio
Universitat Pompeu Fabra
Barcelona, Spain
ernest.montbrio@upf.edu

Alex Roxin
Centre de Recerca Matematica
Bellaterra (Barcelona), Spain
aroxin@crm.cat

MS133

A Bifurcation of the Kuramoto Model on Networks

For the mean-field limit of a system of globally coupled phase oscillators defined on networks, a bifurcation from the incoherent state to the partially locked state at the critical coupling strength is investigated based on the generalized spectral theory. This reveals that a network topology affects the dynamics through the eigenvalue problem of a certain Fredholm integral operator which defines the structure of a network.

Hayato Chiba
Institute of Mathematics for Industry
Kyushu University
chiba@imi.kyushu-u.ac.jp

MS133

Bumps in Small-World Networks

We consider a network of coupled excitatory and inhibitory theta neurons which is capable of supporting stable spatially-localised "bump" solutions. We randomly add long-range and simultaneously remove short-range connections within the network to form a small-world network and investigate the effects of this rewiring on the existence and stability of the bump solution. Two limits are considered in which continuum equations can be derived; bump solutions are *fixed points* of these equations. We can thus use standard numerical bifurcation analysis to determine the stability of these bumps and to follow them as parameters (such as rewiring probabilities) are varied. Under some rewiring schemes bumps are quite robust, whereas in other schemes they can become unstable via Hopf bifurcation or even be destroyed in saddle-node bifurcations.

Carlo R. Laing
Massey University
Auckland
c.r.laing@massey.ac.nz

MS133

**The Mean Field Limit of the Kuramoto Model on

Convergent Graph Sequences

Mathematical analysis of many interesting dynamical effects in systems of coupled oscillators relies on the mean field equation formally derived in the limit, as the number of oscillators goes to infinity. Examples include the onset of synchronization in the Kuramoto model with distributed intrinsic frequencies and emergence and bifurcations of chimera states. In this talk, we discuss the derivation and rigorous justification of the mean field limit for the Kuramoto model on convergent families of certain deterministic and random graphs, including Erdős-Rényi and small-world graphs.

Georgi S. Medvedev
Drexel University
medvedev@drexel.edu

MS133

Bifurcations Mediating Appearance of Chimera States

Coherence-incoherence patterns, better known as 'chimera states', are complex dynamical regimes observed in spatially homogeneous systems of nonlocally coupled oscillators. In many cases they can be adequately represented by relatively simple solutions, e.g. rotating or traveling waves, of a certain partial integro-differential equation. Bifurcation analysis and continuation of these solutions is usually a difficult problem, because of the critical continuous spectrum of the corresponding linearized operator. In this talk, I will discuss mathematical challenges concerned with the consideration of chimera states and show their possible solution in a few special cases motivated by recent research in the field.

Oleh Omel'chenko
Weierstrass Institute
Oleh.Omelchenko@wias-berlin.de

MS134

Introduction, Exact Results for Globally-Coupled Theta Neurons, and Extensions

I will provide an introduction to the Ott-Antonsen ansatz method of obtaining the asymptotic collective behavior of globally-coupled oscillators and its application to networks of theta neurons, and review a number of extensions of this work.

Ernest Barreto
George Mason University
Krasnow Institute
ebarreto@gmu.edu

MS134

Next Generation Neural Field Modelling

Neural field models are actively used to describe wave propagation and bump attractors at a tissue level in the brain. Although motivated by biology, these models are entirely phenomenological in nature. They are built on the assumption that the neural tissue is synchronous, and hence, cannot account for changes in the underlying synchrony patterns. It is customary to use spiking neural network models when examining within population synchronisation. Unfortunately, these high dimensional models are notoriously hard to gain insight from. In this talk I will consider the θ-neuron model, which has recently been shown to admit to an exact mean-field description for instantaneous pulsatile interactions. I will show that the inclusion of space and a more realistic synapse model leads to a similar redused model that has many of the features of a standard neural field model coupled to a further dynamical equation that describes the evolution of network synchrony. Both Turing instability analysis and numerical continuation software were used to explore the existence and stability of spatiotemporal patterns in the system.

Aine Byrne
University of Nottingham
University of Nottingham
aine.byrne@nottingham.ac.uk

Stephen Coombes
University of Nottingham
stephen.coombes@nottingham.ac.uk

Daniele Avitabile
School of Mathematical Sciences
University of Nottingham
Daniele.Avitabile@nottingham.ac.uk

MS134

Weakly Coupled Oscillators in a Slowly Varying World

We extend the theory of weakly coupled oscillators to incorporate slowly varying inputs and parameters. We employ a combination of regular perturbation and an adiabatic approximation to derive equations for the phase-difference between a pair of oscillators. We apply this to the simple Hopf oscillator and then to a biophysical model. The latter represents the behavior of a neuron that is subject to slow modulation of a muscarinic current such as would occur during transient attention through cholinergic activation. Our method extends and simplifies the recent work of Kurebayashi 2013 to include coupling. We apply the method to an all-to-all network and show that there is a waxing and waning of synchrony of modulated neurons.

Youngmin Park
University of Pittsburgh
yop6@pitt.edu

Bard Ermentrout
University of Pittsburgh
Department of Mathematics
bard@pitt.edu

MS134

Exact Low-Dimensional Mean-Field Dynamics of Neuronal Networks

An urgent challenge in neuroscience is to properly describe the collective dynamical behavior of networks of spiking neurons. Recently, an exact correspondence has been established between the macroscopic firing rate of the network and its underlying microscopic state. Montbrió and co-workers [PRX 5, 2015] showed for a network of quadratic integrate-and-fire (QIF) neurons that an effective coupling between firing rate and mean membrane potential prescribes the networks evolution. This low-dimensional formulation, however, requires an extension of the Ott-Antonsen (OA) ansatz for parameter-dependent phase oscillator networks. This is mandatory to describe the macroscopic states of the QIF neurons. We provide a proof that the dynamics of such parameter-dependent systems reduces to the attracting OA manifold. By that the OA ansatz becomes applicable to physiologically realistic oscillator networks.

Bastian Pietras
Vrije Universiteit Amsterdam
Lancaster University
b.pietras@vu.nl

MS135

Extracting Information Flow Between Animals in the Wild

Social animals exhibit collective behavior wherein they negotiate to reach an agreement, for example to coordinate motion and synchronize migration. Bats are unique among such social animals in that they use active sensory echolocation or "bio-sonar', that is, they emit ultrasonic waves and sense echoes to detect and navigate surroundings. In real bat swarms, understanding navigational leadership roles is a challenge, and quantitative assessment of leadership appears to be an entirely untouched area of study. Given the broadcast nature of bio-sonar, the active sensing of one individual can directly influence the motion of others, making the directionality of leadership unclear. Here, we seek to understand navigational leadership in bats from direct observation of bat swarms in flight. Small groups of bats were continuously tracked in a mountain cave in Shandong Province, China, from which 3D path points are extracted and converted to 1D curvature time series. We explore two recent tools from dynamical systems to extract causal relationships between these time series, namely transfer entropy and convergent cross mapping. These tools identify the direction of information transfer between a pair of bats flying together, which allows us to answer the question of whether individuals fly independently of each other or interact to plan flight paths. We find that the identified causal relationships between bats is sensitive to the selected mathematical tools and parameters.

Nicole Abaid, Subhradeep Roy
Virginia Polytechnic Institute and State University
nabaid@vt.edu, sdroy@vt.edu

MS135

Information and Prediction Limits in Online Social Activity

Massive datasets of human activity are now available, revolutionizing research on human dynamics and computational social science. We study the online posts of thousands of Twitter users and their followers. Information flows across the Twitter network by these posts, but it is unclear how much information flows, how much influence do users have on one another, and if we can accurately measure these effects. Treating each Twitter user's text stream as a symbolic time series, the entropy rate measures how much information about a future word choice is available in the past history. We apply theorems from data compression to estimate a "correlated' entropy that accounts for both temporal ordering and long-range correlations in the data. The correlated entropy rate estimates the inherent uncertainty about someone's future word choice. Crucially, this technique can also capture social information transfer between pairs of users (denoted egos and alters), via a cross-entropy that estimates how much information about the ego's future word choice is present in the alter's past words. Some alters contain nearly as much information about the ego as the ego itself, but other ego-alter pairs show little information flux. Taken together, these results provide new quantitative bounds on information transfer in social networks, useful for better understanding the spread of ideas and influence in human populations.

James Bagrow
Department of Mathematics & Statistics
University of Vermont
james.bagrow@uvm.edu

Lewis Mitchell
University of Adelaide
lewismitchell1984@gmail.com

MS135

Inferring Influence and Leadership in Mobile Animal Groups

Most models of collective moment (e.g., flocking, schooling) assume that individuals follow identical behavioral rules. However, in reality individuals almost certainly vary, for example in rank, internal state or behavioral type. Recent advances in GPS and automated tracking technologies are yielding fine-scale trajectories for each individual within mobile animals groups. Here we apply information theoretic measures, specifically optimized causation entropy, to sets of trajectories of collectively moving animals to infer leadership from differential information flow, in a variety of taxa, including storks, bison and baboons. Using the inferred influence networks, we explore whether an individuals position in the influence network is related to individual traits, such as size, age, experience, dominance or spatial position in the group. In contrast to previous results, which found democratic decision making in animal groups, we find evidence for leadership according to social rank, by applying our less subjective measures to the same data.

Andrew Berdahl
Santa Fe Institute
berdahl@santafe.edu

Joshua Garland
University of Colorado at Boulder
joshua@santafe.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

Erik Bollt
Clarkson University
bolltem@clarkson.edu

MS135

Network Flux based on Directed Links in Spatially Embedded Climate Networks

Abstract Not Available At Time Of Publication.

Ugur Ozturk
Potsdam Institute for Climate Impact Research
Institute of Earth and Environmental Science
oeztuerk@pik-potsdam.de

MS136

Cell Based Modelling of Tissue Size Control in the

Drosophila Embryonic Epidermis

Embryogenesis is an extraordinarily robust process, exhibiting the ability to control tissue size and repair patterning defects in the face of environmental and genetic perturbations. Understanding developmental control mechanisms requires studying multiple concurrent processes that make up morphogenesis, including the spatial patterning of cell fates and apoptosis, as well as cell intercalations. Here, we develop a computational model that aims to understand aspects of the robust pattern repair mechanisms of the Drosophila embryonic epidermal tissues. Size control in this system has previously been shown to rely on the regulation of apoptosis rather than proliferation; however, to date little work has been carried out to understand the role of cellular mechanics in this process. We employ a vertex model of an embryonic segment to test hypotheses about the emergence of this size control. Comparing the model to previously published data across wild type and genetic perturbations, we show that passive mechanical forces suffice to explain the observed size control in a segment of the epidermis. However, observed asymmetries in cell death frequencies across the segment are demonstrated to require patterning of cellular properties in the model. Finally, we propose multiple experiments that allow to distinguish distinct forms of mechanical regulation in the model.

Jochen Kursawe
University of Oxford
kursawe@maths.ox.ac.uk

MS136

The Dynamics of Colonic Crypt Dysplasia

Colorectal cancer is the third most common cancer in the UK and USA, with over 170,000 new cases reported each year. These cancers are thought to originate in the crypts that reside along the surface of the intestines. The crypts are small test-tube like depressions of epithelial cells, containing both intestinal stem cells and their progeny, the proliferation of which cause a total renewal of the intestinal lining approximately every 5 days.
This talk will focus on how nonlinear multiscale mathematical models allow us to better understand the dysplastic crypt dynamics that lead to the development of colorectal cancers. The concept of multiscale modelling in this case relates to the inclusion of cell-level mechanical behaviours, such as cell-cell adhesion and cell division, as well as subcellular processes, such as individual cell-cycle models and gene regulatory networks, to create a more complete model of the crypt system. In particular, we will show how the inclusion of physiologically realistic contact inhibition related behaviours, including cell apoptosis, affects the collective cell dynamics, and ultimately how mutations at the microscopic level lead to different dysplastic macroscopic dynamics.

Daniel Ward
University of Bristol
dw0293@bristol.ac.uk

Lucia Marucci
Telethon Institute of Genetics and Medicine, Naples, Italy
lucia.marucci@bristol.ac.uk

Martin Homer
University of Bristol
Department of Engineering Mathematics
martin.homer@bristol.ac.uk

MS136

Optimal Chemotherapy Scheduling Based on a Pair of Collaterally Sensitive Drugs

Despite major strides in the treatment of cancer, the development of drug resistance remains a major hurdle. To address this issue, researchers have proposed sequential drug therapies with which the resistance developed by a previous drug can be relieved by the next one, a concept called collateral sensitivity. Inspired by such studies, we develop multiscale dynamical models and study the effect of sequential chemotherapy utilising a pair of drugs (A-type, B-type) switched in turn within the therapy schedule. An important assumption in our model is that a tumor is comprised by two types of cell groups, A-resistant and B-resistant, each of which is resistant to the indicated drug and sensitive to the other. Based on a population based ODE system, we determined that the optimal treatment strategy consists of two stages: (i) the initial stage in which a chosen better drug is utilised until a specific time point, T, and afterward; (ii) a combination of the two drugs switched in turn with a definite ratio in duration, k. Of note, we prove that the initial period, in which the first drug is administered, T, is shorter than the period in which remains effective, contrary to clinical intuition. Beyond our analytic results, we explore an individual based stochastic model and present the distribution of extinction times for the classes of solutions found. Taken together, our results suggest opportunities to improve chemotherapy scheduling in clinical oncology.

Nara Yoon
Case Western Reserve University
nxy47@case.edu

Robert Vander Velde
University of South Florida
rvandervelde@health.usf.edu

Andriy Marusyk
H Lee Moffitt Cancer Center and Research Institute
andriy.marusyk@moffitt.org

Jacob G. Scott
Cleveland Clinic Lerner Research Institute
scottj10@ccf.org

MS136

Multiscale Agent-Based Models Predict Emergent Dynamics of Heterogeneous Tumor Growth

Computational modeling is an essential tool for integrating and understanding complex biological systems. With increasingly high-resolution, high-throughput, and dynamic experimental data, we are able to develop better informed models to interrogate the complex, heterogeneous, and multiscale nature of cellular microenvironments. We employ agent-based models (ABMs) as an intuitive, modular, and flexible framework to study emergence in heterogeneous cell populations. ABMs utilize dynamic cellular agents that can change state and location over time. Cell states are governed by intracellular agent rules, interactions with neighboring agents, and the local microenvironment. Using this platform, we investigate the impact of intracellular network dynamics on intercellular signaling in the context of cancer. Preliminary results demonstrate how

tumor growth and shape are sensitive to parameters governing glucose uptake and consumption, suggesting that our model is able to recover the importance of metabolic deregulation, a known hallmark of cancer. Our multi-scale, multi-class simulations help interrogate how the whole is greater than the sum of its parts by predicting emergent cell population dynamics from simple cellular rules. We believe such insights are critical for identifying effective drug targets and designing personalized, dynamic therapeutic strategies.

Jessica Yu
Chemical & Biological Engineering
Northwestern University
jessicayu2014@u.northwestern.edu

Neda Bagheri
Chemical and Biological Engineering
Northwestern University
n-bagheri@northwestern.edu

MS137

Oblique Stripes in a Triggered Swift-Hohenberg Equation

Externally mediated, or triggered, spatial patterns have become a topic of recent interest in many fields, where researchers wish to harness natural pattern forming processes to form novel and functional materials. Such triggering mechanisms can be modeled in the prototypical Swift-Hohenberg equation, posed on the plane, with a planar inhomogeneity which travels horizontally across the domain, converting the trivial homogeneous equilibrium into an unstable state. We prove the existence of pattern-forming modulated traveling waves in this system which leave behind oblique, or slanted, stripes of long transverse wavelength. We employ a functional analytic approach which regularizes the singular limit of small transverse wavenumber to obtain such oblique solutions as a continuous perturbation of one-dimensional trigger fronts, which leave behind stripes parallel to the interface of the inhomogeneity.

Ryan Goh
Mathematics and Statistics
Boston University
rgoh@bu.edu

Arnd Scheel
University of Minnesota
scheel@umn.edu

MS137

Waves and Obstacles in Square Lattices

We study dynamical systems posed on a square lattice, with a special focus on the behaviour of basic objects such as travelling corners and travelling waves under (potentially large) perturbations of the wave and the underlying spatial lattice. Such travelling structures satisfy functional differential equations of mixed type, which can be seen as generalizations of delay equations in the sense that both delays and advances in the arguments are allowed.

Hermen Jan Hupkes
University of Leiden
Mathematical Institute
hhupkes@math.leidenuniv.nl

Erik Van Vleck
Department of Mathematics
University of Kansas
erikvv@ku.edu

Aaron Hoffman
Franklin W. Olin College of Engineering
aaron.hoffman@olin.edu

Leonardo Morelli
University of Leiden
l.morelli@math.leidenuniv.nl

MS137

Phase Separation from Directional Quenching and Unbalanced Patterns in Cahn-Hilliard and Allen-Cahn Equations

In this talk I describe the effect of directional quenching on patterns formed in simple bistable systems such as the Allen-Cahn and the Cahn-Hilliard equation on the plane. Directional quenching is considered as an externally triggered change in system parameters, changing the system from monostable to bistable across an interface; numerically and experimentally, one can see patterns forming in the bistable region, in particular as the trigger progresses and increases the bistable region. I will discuss existence and non-existence results of single interfaces and striped patterns. Joint work with Arnd Scheel.

Rafael Monteiro da Silva
School of Mathematics
University of Minnesota
rmonteir@umn.edu

MS137

A Dynamical Approach to Elliptic Equations on Bounded Domains

We develop the method of spacial dynamics, and obtain a system of operator-valued ODEs equivalent to elliptic problems on bounded domains. Let $\Omega \subset \mathbb{R}^n$ be a bounded domain, and suppose u satisfies the equation $-\Delta u + Vu = \lambda u$ on Ω. When the domain is deformed through a one-parameter family Ω_t, the Cauchy data of u on $\partial\Omega_t$ satisfies a Hamiltonian evolution equation. Moreover, this equation admits an exponential dichotomy with the unstable subspace at time t corresponding to the Cauchy data of weak solutions to the PDE on Ω_t as Ω is deformed smoothly to a point. (Joint work with Margaret Beck, Graham Cox, Chris Jones and Yuri Latushkin)

Alim Sukhtayev
Department of Mathematics
Indiana University Bloomington
alimsukh@iu.edu

MS138

Coarse Graining under Prevalent Embeddings

This talk considers high dimensional drift-diffusion systems, whose essential dynamics is constricted to a smooth, low-dimensional, but unknown manifold. Using the well-known Whitney embedding theorem, I describe how the analysis of prevalent, i.e. almost arbitrary embeddings of the dynamics into a low-dimensinal euclidean space is sufficient to not only find the manifold, but to construct reduced drift and diffusion terms to coarse-grain the original dynamics.

Andreas Bittracher
Center for Mathematics
TU Munich
bittracher@mi.fu-berlin.de

MS138

Diffusion Forecast: A Nonparametric Probabilistic Modeling of Dynamical Systems

I will discuss a nonparametric modeling approach for forecasting stochastic dynamical systems on smooth manifolds embedded in Euclidean space. In the limit of large data, this approach converges to a Galerkin projection of the semigroup solution of the backward Kolmogorov equation of the underlying dynamics on a basis adapted to the invariant measure. This approach, which we called the diffusion forecast, allows one to evolve the probability distribution of non-trivial dynamical systems with an equation-free modeling.

John Harlim
Pennsylvania State University
jharlim@psu.edu

MS138

Complex Dynamics in Multiscale Systems

Understanding the evolution of complex multiscale systems is crucial from a fundamental but also the applications' point of view. For instance, many engineering systems are complex and multiscale and understanding their dynamics has the potential to predict a specific system's behavior, engineer its design and build-in response to arrive at a highly optimal and robust system. We combine elements from homogenization theory, nonlinear science, statistical physics, critical phenomena and information theory to develop a number of novel and generic methodologies that enable us to undertake the rigorous and systematic study of the emergence of complex behavior in multiscale systems. The methodologies are exemplified with paradigmatic prototypes from different classes of complex systems such as interface dynamics in disordered media, convectively unstable open flows and stochastic multiscale phenomena in noisy spatially extended systems and diffusion in multiscale potentials. [Joint work with Marc Pradas (Open), Markus Schmuck (Heriot Watt), Dmitri Tseluiko (Loughborough), Grigorios A. Pavliotis (Imperial) and Andrew Duncan (Sussex)]

Serafim Kalliadasis
Department of Chemical Engineering
Imperial College London
s.kalliadasis@imperial.ac.uk

MS138

Information-Theoretic Methods for Coarse-Graining Stochastic Dynamics

We discuss information-theoretic metrics for obtaining optimized coarse-grained molecular models for both equilibrium and non-equilibrium molecular dynamics. The presented approach compares microscopic behavior of molecular systems to parametric or non-parametric coarse-grained systems using the relative entropy between distributions on the path space. The use of goal-oriented information-theoretic inequalities allows us to bound the error for quantities of interest. The methods become entirely data-driven when the microscopic dynamics are replaced with corresponding correlated data in the form of time series. We present applications of the method to coarse-graining polymers, and to defining empirical potentials from quantum mechanical data in materials modeling.

Petr Plechac
University of Delaware
Department of Mathematical Sciences
plechac@math.udel.edu

MS139

Shannon Entropy Estimation Based on Chaotic Attractor Reconstruction for a Semiconductor Laser

State-space reconstruction of chaotic attractors is investigated for deducing the randomness generated by an optically injected semiconductor laser. The attractors are reconstructed using the intensity time series from both simulations and experiments. The time-dependent exponent is adopted for estimating the divergence between nearby trajectories, thereby verifying the effective noise amplification by chaotic dynamics. After discretization for obtaining the output bits, the Shannon entropies continually generated by the laser are estimated. Here, the effect of postprocessing on the randomness of the output bits is investigated by evaluating the Shannon entropies. The role of a delayed exclusive-or operation is investigated, where the time-dependent exponents as well as the Shannon entropies are affected. The results fundamentally confirm the provision of non-deterministic randomness by the chaotic lasers. Practical tests for randomness at a combined output bit rate of 200 Gbps are successfully conducted.

Xiao-Zhou Li, Jun-Ping Zhuang, Song-Sui Li
City University of Hong Kong
xiaozli4-c@my.cityu.edu.hk, jzhuang7-c@my.cityu.edu.hk, songsui.li@my.cityu.edu.hk

Sze-Chun Chan
City University of Hon
Department of Electronic Engineering
scchan@cityu.edu.hk

MS139

Progress in Random Number Generation with Chaotic Lasers

Fast physical random number generators based on chaotic lasers have been investigated intensively for a decade. The generation rate of random number generators based on chaotic laser dynamics has been progressing over Terabit per second (Tb/s). In addition, photonic integrated circuits (PICs) are promising devices to minimize the size of random number generators for practical implementation. We present the recent progress of the speed and the miniaturization of physical random number generators based on chaotic lasers. We experimentally demonstrate ultra-fast physical random number generation with the bandwidth-enhanced chaos obtained from three-cascaded semiconductor lasers. We generate physical random numbers from the bandwidth-enhanced chaos by using a multi-bit extraction method. We achieve the maximum generation rate of 1.2 Tb/s for the physical random bit sequences whose randomness is verified by the standard statistical tests of randomness. We also fabricate PICs with short external cavity lengths to perform the miniaturization of physical random number generators. We use PICs with different external cavity lengths (1-10 mm) to generate random bit sequences.

These PICs are promising miniature entropy sources for the integration of random number generators for applications in information security and numerical computations.

Atsushi Uchida, Kazusa Ugajin, Yuta Terashima, Keigo Yoshiya
Department of Information and Computer Sciences
Saitama University
auchida@mail.saitama-u.ac.jp, s14mm305@mail.saitama-u.ac.jp, s15mm318@mail.saitama-u.ac.jp, s16mm336@mail.saitama-u.ac.jp

MS139

Real-Time Fast Physical Random Number Generators

Physical random number generators (RNGs) have great applications in cryptography and secure communication. Due to the high bandwidth and large amplitude fluctuation, chaotic laser is recently viewed as an ideal entropy source to solve the problem of limited low rates confronted by conventional RNGs. In this report, we focus on the real-time implementation of physical RNGs based on laser and electrical chaos. Specifically, we will present our works from two aspects: one is how to generate the ultra-broad or white chaos using semiconductor laser diodes or circuits, and the other is the real-time extraction of ultrafast random numbers involving electrical and all-optical methods. Based on these researches, several types of RNG prototypes or modules are also be presented, whose maximum real-time rate can reach a level of 10 Gb/s.

Yuncai Wang
Taiyuan University
Institute of Optoelectronic Engineering
wangyc@tyut.edu.cn

Pu Li, Anbang Wang, Jianguo Zhang, Xianglian Liu, Yanqiang Guo, Luxiao Sang
Taiyuan University of Technology
Institute of Optoelectronic Engineering
lipu8603@126.com, wanganbang@tyut.edu.cn, iking79@163.com, liuxianglian@tyut.edu.cn, guoyanqiang@tyut.edu.cn, sangluxiao@163.com

MS139

Quantum Random Number Generator: Speed and Security

Quantum random number generator (QRNG) is an important approach to generate true random numbers that are unpredictable, irreproducible, and unbiased. Speed is one of the key QRNG parameters. In this talk, we will first introduce the typical QRNG schemes such as beam splitters, photon arrival times, vacuum fluctuations, and laser phase fluctuations. Then we will present our recent progresses on QRNG implementations. In QRNGs, the randomness relies on the accurate characterization of its devices. However, device imperfections and inaccurate characterizations can result in wrong entropy estimation and bias in practice, which highly affects the genuine randomness generation. Very recently the concept of measurement-device-independent (MDI) QRNG has been proposed, and we have experimentally implemented a MDI-QRNG for the first time based on time-bin encoding to achieve certified quantum randomness even when the measurement devices are uncharacterized and untrusted. Our implementation with an all-fiber setup provides an approach to construct a practical MDI-QRNG with trusted but error-prone devices.

Jun Zhang
University of Science and Technology of China
Hefei National Laboratory for Physical Sciences at Microscal
zhangjun@ustc.edu.cn

MS140

Delay Embeddings and the Spectra of Koopman Operators

The Koopman operator induced by a dynamical system is inherently linear and provides an alternate method of studying many properties of the system, including attractor reconstruction and forecasting. Koopman eigenfunctions represent the non-mixing component of the dynamics. They factor the dynamics, which can be chaotic, into quasiperiodic rotation on tori. We will describe a method in which these eigenfunctions can be obtained by applying an integral operator, which behaves as a projection operator. The underlying idea is a data-driven method of using an integral operator approximation of the Laplace-Beltrami operator. We will show that incorporating a large number of delay coordinates in constructing the kernel of the operator results in the creation of a projection into the discrete spectrum subspace, in the limit of infinitely many delay coordinates.

Suddhasattwa Das, Dimitrios Giannakis
Courant Institute of Mathematical Sciences
New York University
dass@cims.nyu.edu, dimitris@cims.nyu.edu

MS140

Nonparametric Reconstruction from Noisy Time Series: The Kalman-Takens Method

Modern methods of data assimilation rely on a key assumption: that a mathematical model of the physical system is known. In absence of a model, outright implementation of standard techniques such as ensemble Kalman filtering is impossible. In this talk, I will present a novel approach to filtering noisy time series when a model is not known. This nonparametric approach to filtering merges the key ideas behind Takens' method of attractor reconstruction and the Kalman filter. The resulting Kalman-Takens filter replaces the model with dynamics reconstructed from delay coordinates, while using the Kalman update formulation to assimilate new observations. I will show that this model-free approach to filtering is able to handle significant observational and dynamical noise in identifying underlying dynamics.

Franz Hamilton
Center for Quantitative Sciences in Biomedicine
North Carolina State University
fwhamilt@ncsu.edu

MS140

Topological Symmetries: Quasiperiodicity and Its Application to Filtering and Classification Problems

Chirped sinusoids and interferometric phase plots are functions that are not periodic, but are the composition of a smooth function and a periodic function. These functions factor into a pair of maps: from their domain to a circle, and from a circle to their codomain. One can easily imagine replacing the circle with other phase spaces to obtain a general quasiperiodic function. Under appropriate restrictions, each quasiperiodic function has a unique universal factorization. Quasiperiodic functions can therefore be classified based on their phase space and the phase function mapping into it. This talk will present a two-stage topological algorithm for recovering an estimate of a quasiperiodic function from a set of noisy measurements. By respecting an estimate of the phase space and phase function, the algorithm avoids creating distortion even when it uses a large number of samples for the estimate of the function.

Michael Robinson
Department of Mathematics and Statistics
American University
michaelr@american.edu

MS140

Stabilizing Embedology: When Do Delay-Coordinate Maps Preserve Geometry?

The efficacy of delay-coordinate mapping has long been supported by Takens' embedding theorem, which guarantees that delay-coordinate maps use the time-series output to provide a reconstruction of the hidden state space that is a one-to-one embedding of the system's attractor. While this topological guarantee ensures that distinct points in the reconstruction correspond to distinct points in the original state space, it does not characterize the quality of this embedding or illuminate how the specific problem details affect the reconstruction. We extend Takens' result by establishing conditions under which delay-coordinate mapping is guaranteed to provide a stable embedding of a system's attractor. Beyond only preserving the attractor topology, a stable embedding preserves the attractor geometry by ensuring that distances between points in the state space are approximately preserved. In particular, we find that delay-coordinate mapping stably embeds an attractor of a dynamical system if the stable rank of the system is large enough to be proportional to the dimension of the attractor. The stable rank reflects the relation between the sampling interval and the number of delays in delay-coordinate mapping. Our theoretical findings give guidance to choosing system parameters, echoing the trade-off between irrelevancy and redundancy that has been heuristically investigated in the literature.

Armin Eftekhari
Alan Turing Institute
armin.eftekhari@gmail.com

Han Lun Yap
Georgia Institute of Technology
yaphanlun@gatech.edu

Michael B. Wakin
Dept. of Electrical Engineering and Computer Science
Colorado School of Mines
mwakin@mines.edu

Chris Rozell
Georgia Institute of Technology
crozell@gatech.edu

MS141

Objective Detection of Kinematic and Magnetic Vortices in Astrophysical Plasmas

Previous works have demonstrated that the technique of hyperbolic Lagrangian coherent structures is useful for analyzing the dynamics of velocity and magnetic fields in numerical simulations and satellite observations of astrophysical plasmas such as solar photospheric turbulence. An accurate detection of the boundary of coherent structures in velocity and magnetic fields of a plasma is fundamental for the study of astrophysical turbulence, for example, the determination of the front and rear boundary layers of magnetic flux ropes in the solar wind is essential for locating the preferential sites for the genesis of interplanetary intermittent turbulence. In this work we apply the approach of rotational Lagrangian coherent structures to detect kinematic vortices in 3D magnetohydrodynamic simulations of an astrophysical dynamo. The objective kinematic vortices are given by tubular level surfaces of the Lagrangian Averaged Vorticity Deviation (LAVD), the trajectory integral of the normed difference of the vorticity from its spatial mean. In addition, we adapt the LAVD technique to use it on magnetic fields and propose the method of Integrated Averaged Current Deviation (IACD) to determine precisely the boundary of magnetic vortices. The relevance of objective kinematic and magnetic vortices in solar plasmas is discussed.

Erico L. Rempel
Institute of Aeronautial Technology, Brazil
erico_rempel@yahoo.com.br

Abraham C. Chian
National Institute for Space Research (INPE), P.O. Box 515,
Sao Jose dos Campos, SP, Brazil
abraham.chian@adelaide.edu.au

Francisco J. Beron-Vera
RSMAS, University of Miami
fberon@rsmas.miami.edu

Sandor Szanyi
5Institute for Mechanical Systems, Department of Mechanical
szanyis@ethz.ch

George Haller
ETH, Zurich, Switzerland
georgehaller@ethz.ch

Tiago F. P. Gomes
National Institute for Space Research (INPE), Brazil
tiagofpgomes@gmail.com

Suzana S. A. Silva
Institute of Aeronautial Technology, Brazil
suzana.seas@gmail.com

MS141

Application of Dynamical Systems Approach to Lagrangian Separation in Laminar and Turbulent Flows

In fluid mechanics, the separation phenomenon is as common as unpredictable. It causes the aerodynamic stall of aircraft wings, reduces the performance of turbomachines and limits the efficiency of hydraulic turbines. Although it has long been known, to date we can neither detect nor predict it with a unique and universal way. While in

two-dimensional steady flows Prandtl stated that the separation point coincides with the location on a solid wall where fluid friction vanishes, it turns out that in presence of three-dimensionality or unsteadiness this criterion is not valid. When separation occurs, the fluid flowing along the wall suddenly detaches from the boundary. Based on this ejection process, several theories have emerged to detect separation but remain difficult, if not impossible, to apply in practice, so that the Prandtl criterion is still widely used because of its simplicity. The Lagrangian theory proposed by Haller in 2004 revisited the concept of unsteady separation by defining a material instability induced by an unstable manifold, without requiring to solve Navier-Stokes or boundary layer equations. Based entirely on kinematic arguments, this theory may in principle be applied to turbulent flows, which has never been verified. In this study, we propose to explore the nature of separation in 2D unsteady flows. The Lagrangian approach is applied from simple vortical flows to numerical data derived from turbulence simulations.

Seán Crouzat
Polytechnique Montréal, Canada
sean.crouzat@polymtl.ca

Jérôme Vétel
École Polytechnique de Montréal, Canada
jerome.vetel@polymtl.ca

MS141

Lagrangian Coherent Structures and DNS with Discontinuous Galerkin Methods

High-fidelity numerical tools based on high-order Discontinuous-Galerkin (DG) methods and Lagrangian Coherent Structure (LCS) theory for the study of separated, vortex-dominated flows are discussed. A numerical framework is presented that couples a higher-order DG-DNS solver with time-dependent analysis of the flow through LCS . At heart of this framework lies an algorithm that computes Finite-Time Lyapunov Exponent (FTLE) fields simultaneously with DNS and with spectral accuracy. The algorithm is applied to investigate the role of LCS control fo unsteady separated flow over a NACA 65-(1)412 airfoil at a free-stream Reynolds number of Re=20,000.

Gustaaf Jacobs
Department of Aerospace Engineering
San Diego State University
gjacobs@mail.sdsu.edu

MS141

Ephemeral Transport Boundaries in Geophysical Fluid Flows

Dynamical Systems has been spectacularly successful in partitioning mesoscale oceanic and atmospheric transport pathways. Here processes operate on large space and long time scales. However, there is increasing evidence in the ocean that processes acting in the submesoscale can have substantial impact on the mesoscale circulation. Specific concerns are the facts that at the submesoscale the fluid is no longer two-dimensional incompressible and dynamical processes operate on time scales of hours to days. Thus the question arises about the efficacy of standard dynamical systems methods for identifying transport boundaries at these scales. To address this issue we developed a dynamically balanced model that includes three-dimensional flow in a rotating and stratified setting. The model allows for submesoscale processes such as internal waves and surface forcing by the wind. Here we discuss some preliminary results on identifying transport pathways in this environment. The results generally are encouraging, but it is critical that the vertical velocity be included in calculations.

Denny Kirwan, Henry Chang, Helga S. Huntley
University of Delaware
adk@udel.edu, changh@udel.edu, helgah@udel.edu

MS142

Resynchronization of Circadian Oscillators and the East-West Asymmetry of Jet-Lag

Cells in the brain's Suprachiasmatic Nucleus (SCN) are known to regulate circadian rhythms in mammals. We model synchronization of SCN cells using the forced Kuramoto model, which consists of a large population of coupled phase oscillators (modeling individual SCN cells) with heterogeneous intrinsic frequencies and external periodic forcing. Here, the periodic forcing models diurnally varying external inputs such as sunrise, sunset, and alarm clocks. We reduce the dimensionality of the system using the ansatz of Ott and Antonsen and then study the effect of a sudden change of clock phase to simulate cross-time-zone travel. We estimate model parameters from previous biological experiments. By examining the phase space dynamics of the model, we study the mechanism leading to the difference typically experienced in the severity of jet-lag resulting from eastward and westward travel.

Zhixin Lu
University of Maryland
zhixin.lu1988@gmail.com

Kevin Klein-Cardena
DePaul University
kevinkleinc@outlook.com

Steven Lee
Brooklyn CUNY
ls0619@bcmail.brooklyn.cuny.edu

Thomas Antonsen Jr., Michelle Girvan
University of Maryland
antonsen@umd.edu, girvan@umd.edu

Edward Ott
University of Maryland
Inst. for Research in Electronics and Applied Physics
edott@umd.edu

MS142

Symmetric States Requiring System Asymmetry

Spontaneous synchronization has long served as a paradigm for behavioral uniformity that can emerge from interactions in complex systems. When the interacting entities are identical and their coupling patterns are also identical, the complete synchronization of the entire network is the state inheriting the system symmetry. As in other systems subject to symmetry breaking, such symmetric states are not always stable. In this presentation, I will report on the discovery of the converse of symmetry breaking—the scenario in which complete synchronization is not stable for identically coupled identical oscillators but becomes stable when, and only when, the oscillator parameters are judiciously tuned to nonidentical values, thereby breaking the system symmetry to preserve the state symmetry. Aside from demonstrating that diversity can facilitate and even be required for uniformity and consensus, this suggests a mechanism for convergent forms of pattern formation in which initially asymmetric patterns evolve into symmetric ones.

Takashi Nishikawa, Adilson E. Motter
Northwestern University
t-nishikawa@northwestern.edu, motter@northwestern.edu

MS142

Two Types of Quasiperiodic Partial Synchrony: What Happens When Symmetric States Become Unstable

Population of identical globally coupled oscillators typically exhibits either fully synchronous solution or a splay state. However, quite frequently both these symmetrical states are unstable and the system settles at some intermediate regime, called self-consistent partial synchrony. This state is characterized by a smooth but non-uniform distribution of phases, so that the mean field is non-zero. Another peculiar feature of the dynamics in this regime is quasiperiodicity. We distinguish between two different quasiperiodic states: in the first case the frequency of the mean field is generally incommensurate with that of oscillators; in the second case average frequencies of the mean field and of the oscillators coincide, but the motion of oscillators is additionally modulated by a generally incommensurate frequency. We argue that self-consistent partial synchrony is a general phenomenon. We illustrate two types of quasiperiodic dynamics by different models, including phase oscillators with biharmonic coupling function, nonlinearly coupled Stuart-Landau systems, and linearly coupled Rayleigh and Hindmarsh-Rose oscillators.

Michael Rosenblum
Potsdam University
Department of Physics and Astronomy
mros@uni-potsdam.de

MS142

Chimera and Chimera-Like States in Populations of Nonlocally Coupled Homogeneous and Heterogeneous Chemical Oscillators

We have studied chimera and chimera-like states in populations of photochemically coupled Belousov-Zhabotinsky (BZ) oscillators. Simple chimeras and chimera states with multiple and traveling phase clusters, phase-slip behavior, and chimera-like states with phase waves are described. Simulations with a realistic model of the discrete BZ system of populations of homogeneous and heterogeneous oscillators are compared with each other and with experimental behavior.

Kenneth Showalter
West Virginia University
Department of Chemistry
kshowalt@wvu.edu

MS143

Dynamical Transitions Between a Limit Cycle and a Fix Point in a Saline Oscillator

Density oscillators are simple inexpensive devices that undergo repeated oscillations. These devices can illustrate the principles essential to oscillators driven by concentration gradients (e.g., ion channels). They consist of an outer chamber of light fluid underneath an inner chamber of heavy fluid, and an orifice between the two chambers through which the two fluids of different density can be exchanged under the influence of gravity and a Rayleigh-Taylor instability. Typically, the two fluids are exchanged via oscillatory jets of laminar flow that can last for many hours. For example, when a solution of sodium chloride (NaCl) and deionized water (DI) is placed in the inner chamber and DI in the outer chamber, downward jets of the heavier fluid (NaCl) and upward jets of DI are produced one after the other at a constant frequency. We show in this talk how this limit cycle produced by oscillating unidirectional flows can be perturbed and converted into a fix point solution where a bidirectional flow is present. We use the system to show how this bistable region exist as a function of the hole diameter. We then use a modified Fitzhugh-Nagumo model to describe the experimental results and make a relation between the transitions between limit cycle and fix point as a function of their basins of attractions.

Flavio H. Fenton
Georgia Institute of Technology
flavio.fenton@physics.gatech.edu

Hortencia Gonzales, Humberto Arce
Universidad National Autonoma de Mexico
hortecgg@ciencias.unam.mx, harce@ciencias.unam.mx

MS143

Noise, Chaos and Random Numbers

Random number generation is essential for encryption of information and Monte Carlo simulations. We examine sources and signatures of randomness and determinism in simple optoelectronic nonlinear dynamical systems. Measures of entropy production and dependence on observational precision and time resolution are described. Applications of optoelectronic systems to physical random number generation and assessment are explored and state-of-the-art techniques will be discussed. The role of amplification of intrinsic noise by chaos will be examined and methods to quantify it will be outlined.

Kevin Fei
Harvard University
kevinfei@college.harvard.edu

Joseph Hart
University of Maryland
jhart12@umd.edu

Thomas E. Murphy
University of Maryland, College Park
Dept. of Electrical and Computer Engineering
tem@umd.edu

Rajarshi Roy
University of Maryland
Institute for Research in Electronics and Applied Physics
rroy@glue.umd.edu

MS143

Coherent Structures in the Motion of Reaction

Fronts and Swimming Organisms in Laminar Flows

We present results of table-top experiments that measure burning- and swimming-invariant manifolds (BIMs and SWIMs) that act as one-way barriers that impede the motion of reaction fronts and active tracers (swimming bacteria) in laminar fluid flows. For the reaction front experiments, the flows are 2-D and 3-D chains of vortices, generated by magnetohydrodynamic forcing, and the propagating front is produced by the excitable Belousov-Zhabotinsky chemical reaction. The locations of BIMs are predicted from a model of the velocity field and a set of ordinary differential equations that follows the motion of an element of the front. For the experiments with active tracers, the flow is a 2-D extensional flow in a microfluidic channel, and the tracers are a mutated, "smooth swimming" bacillus subtilis. The locations of predicted SWIMs are verified experimentally by following the trajectories of individual bacteria in the flow. The results of these simplified experiments and the general BIM/SWIM analysis should be applicable to a wide range of systems in which a front or swimmer with a well-defined speed is moving in a fluid flow.

Thomas H. Solomon, Minh Doan, Katie Lilienthal, JJ Simons, Payton Johnsom, Joan Gannon
Department of Physics & Astronomy
Bucknell University
tsolomon@bucknell.edu, mnd004@bucknell.edu, kel014@bucknell.edu, jjs060@bucknell.edu, pmj008@bucknell.edu, jdg021@bucknell.edu

MS143

Jamming in Granular Systems of Regular Polygons

The study of the onset of mechanical stability, known as the jamming transition, of granular systems provides key insights into properties of amorphous materials. A fundamental challenge to understanding this transition is to determine the influence of particle properties. Here, we investigate how nontrivial particle shapes affect the jamming transition as controlled by the packing fraction. Our experiments are performed by compression of two-dimensional arrangements of photoelastic particles, allowing us to visualize force information. To explore the role of particle shape, we systematically change the number of sides of polygonal particles used in the experiments and compare the force chain network, contact number and pressure evolution of compressed systems of polygons to the well-studied systems of disks. We also explore the influence of geometric features, such as face-face contacts and ordering within packings, in connection with the jamming transition.

Cacey Stevens Bester, Yiqiu Zhao
Department of Physics
Duke University
cacey.stevens@phy.duke.edu, yiqiu.zhao@duke.edu

Jonathan Bares
Montpellier University
jb@jonathan-bares.eu

Robert Behringer
Duke University
Center for Nonlinear and Complex Systems, Dept of Physics
bob@phy.duke.edu

MS144

A Path-Integral Approach to Data Assimilation for Mapping Small Neuronal Networks

We present results of simulated experiments to simultaneously estimate properties of individual neurons and synaptic connections in small networks. The calculations are performed via a method of data assimilation (D.A.) that can be derived from a path-integral formulation. The aim in D.A. is to ascertain the predictive power of a model, where the model may contain parameters to be estimated, there may exist multiple sets of parameters that fit the experimental measurements, and the available measurements are sparse. The central consideration is the information content of a measurement. We ask: *which quantities of (from) a system must be measured, to complete the corresponding model?* We perform D.A. via an optimization procedure, where the cost function is cast as the physical Action on a system's path through its state space. Among degenerate parameter sets, the correct set may be identified via its correspondence to the path of least action. We show results of this procedure on two- and three-neuron networks, and the predictive power of the completed models. The long-term aim is to design real laboratory experiments based on this procedure. Such experiments would, in principle, furnish the data required to seek: 1) a possible quantifiable relation between a cell's electrophysiological properties and its functional connectivity within a network, and 2) timescales on which properties commonly identified as parameters may in fact vary.

Eve Armstrong
University of CA, San Diego
University of CA, San Diego
earmstrong@physics.ucsd.edu

MS144

Finite Size Effects and Rare Events in Balanced Cortical Networks

Cortical neuron spiking activity is broadly classified as temporally irregular and asynchronous. Model networks with a balance between large recurrent excitation and inhibition capture these two features, and are a popular framework relating circuit structure and network dynamics, though are traditionally restricted to a single attractor. We analyze paired whole cell voltage-clamp recordings from spontaneously active neurons in mouse auditory cortex slices (Graupner & Reyes, 2013) showing a network where correlated excitation and inhibition effectively cancel, except for intermittent periods when the network shows a macroscopic synchronous event. These data suggest that while the core mechanics of balanced activity are important, we require new theories capturing these brief but powerful periods when balance fails. Recent work by Mongillo et.al. (2012) showed that balanced networks with short-term synaptic plasticity can depart from strict linear dynamics. We extend this model by incorporating finite network size, introducing strong nonlinearities in the firing rate dynamics and allowing finite size induced noise to elicit large scale, yet infrequent, synchronous events. We identify core requirements for system size and network plasticity to capture the transient synchronous activity observed in our experimental data set. Our model properly mediates between the asynchrony of balanced activity and the tendency for strong recurrence to promote macroscopic population dynamics.

Jeffrey Dunworth
Mathematics Department
University of Pittsburgh
jbd20@pitt.edu

Bard Ermentrout
University of Pittsburgh
Department of Mathematics
bard@pitt.edu

Michael Graupner
Universite Paris Descartes
michael.graupner@parisdescartes.fr

Alex Reyes
Center for Neural Science
New York University
reyes@cns.nyu.edu

Brent Doiron
Dept. of Mathematics
Univ. of Pittsburgh
bdoiron@pitt.edu

MS144

Large-Scale Connectome-Based Brain Networks Models of Seizure Spread

Over the past decade we have demonstrated that constraining computational brain network models by structural information obtained from human brain imaging (anatomical MRI, diffusion tensor imaging (DTI)) allows patient specific predictions, beyond the explanatory power of neuroimaging alone. This fusion of an individuals brain structure with mathematical modelling allows creating one model per patient, systematically assessing the modeled parameters that relate to individual functional differences. The model is expressed as neural fields and their dynamics in terms of differential-integral equations, in which the integral kernels represent translationally invariant (local) and variant (global) connectivity. The functions of the brain model allow executing dynamic neuroelectric simulation; further modeling features include refined geometry in 3D physical space; detailed personalized brain connectivity (Connectome); large repertoire of mathematical representations of brain region models, and a complete set of physical forward solutions mimicking commonly used in non-invasive brain mapping including functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG) Electro-encephalography (EEG) and Stereo-oElectroEncephalography (SEEG). So far our large-scale brain modeling approach has been successfully applied to the modeling of the resting state dynamics of individual human brains, as well as aging and clinical questions in stroke and epilepsy.

Viktor Jirsa
Institut de Neurosciences des Systèmes Inserm UMR1106
Aix-Marseille Université
viktor.jirsa@univ-amu.fr

MS144

Clustered Desynchronization of Neural Oscillators

Inspired by the hypothesis that some symptoms of Parkinson's disease are related to pathological synchronization in the motor control region of the brain, there has been interest in finding electrical stimuli which desynchronize neural populations. Recent results on coordinated reset and periodically forced oscillators suggest that forming distinct clusters of neurons may prove to be more effective than achieving complete desynchronization, in particular by promoting plasticity effects that might persist after stimulation is turned off. We propose a single-input low-power control strategy to achieve such clustering, based on the analysis of the reduced phase model for a set of identical neurons.

Jeff Moehlis, Timothy Matchen
Dept. of Mechanical Engineering
University of California – Santa Barbara
moehlis@engineering.ucsb.edu, tmatchen@umail.ucsb.edu

MS145

The Stability and Slow Dynamics of Localized Spot Patterns for the 3-D Schnakenberg Reaction-Diffusion Model

On a bounded three-dimensional domain, we employ a hybrid asymptotic-numerical method to analyze the existence, linear stability, and slow dynamics of localized quasi-equilibrium multi-spot patterns of the Schnakenberg reaction-diffusion model with bulk feed rate A. When A is spatially constant, we illustrate an imperfection-sensitive bifurcation structure of the multi-spot quasi-equilibria, and demonstrate competition and self-replication instabilities whereby spots may annihilate or split into two. When the feed rate A is spatially non-uniform, new equilibrium configurations can be created. In particular, when A is spatially localized, we show that a spot can become pinned at the source point in finite time. Joint work with S. Xie, T. Kolokolnikov, and M.J. Ward.

Justin C. Tzou
University of British Columbia
tzou.justin@gmail.com

MS145

Amoeboid Locomotion in Heterogenous Media

Organisms choose one of various courses of action in response to a wide variety of environmental conditions. How the variety is induced by an external stimulus is an open question. We experimentally found that statistical distribution of passage time across the quinine zone switched from unimodal to bimodal when the periodic perturbation of light stimulation is applied homogeneously in space in addition to the quinine-induced differentiation. This result implies that differentiation of behavioral types is modified step by step through the compounding of stimulation inputs. Based on a mathematical model for cell movement in Physarum plasmodium, we succeeded to reproduce the stimulation-induced differentiation observed in the experiment.

Kei-Ichi Ueda
Faculty of Science, University of Toyama
kueda@sci.u-toyama.ac.jp

Itsuki Kunita
Kumamoto University
kunita@kumamoto-u.ac.jp

Shigeru Kuroda
Research Institute for Electronic Science,

Hokkaido university
shigeru.kuroda@es.hokudai.ac.jp

Dai Akita, Toshiyuki Nakagaki
Hokkaido University
akitad@mail.sci.hokudai.ac.jp, nakagaki@es.hokudai.ac.jp

MS145

Wavenumber Selection Via Spatial Parameter Step

The Swift-Hohenberg (SH) equation is a prototypical, pattern-forming model equation for Turing instability phenomena. We study the SH equation with a space-dependent parameter that renders the medium stable in $x < 0$ and unstable in $x > 0$. We prove the existence of a family of steady-state solutions that represent a transition in space from a homogeneous state to a “striped” pattern state. Solutions in the family vanish as $x \to -\infty$ and are asymptotically periodic as $x \to \infty$. Wavenumbers appearing asymptotically in the family are restricted to a neighborhood of 1 with width depending linearly on the size of the parameter jump. Our methods involve using normal form theory and a co-rotating reference frame to represent the instability in SH by the real Ginzburg-Landau (GL) amplitude equations. The family of solutions is found to leading order as a heteroclinic connection in the GL equations and existence is proved by finding an intersection of unstable and stable manifolds which persists in the SH equation.

Jasper Weinburd
University of Minnesota - Twin Cities
weinburd@umn.edu

Arnd Scheel
University of Minnesota
School of Mathematics
scheel@math.umn.edu

MS145

Title Not Available At Time Of Publication

Abstract Not Available At Time Of Publication.

Shuangquan Xie
Dalhousie University
Department of Mathematics and Statistics
xieshuangquan2013@gmail.com

MS146

Dynamics of Large Networks of FitzHugh-Nagumo Neuronal Models with Heterogeneous Inputs

Large networks of identical nonlinear neuronal oscillators exhibit complex dynamics that depend on network structure and distribution of external input. Mathematical investigation of the dynamics in oscillator networks can help in understanding the behavior of neuronal ensembles in the brain. We implement sufficient conditions for synchronization in networks of FitzHugh-Nagumo (FN) neuronal oscillators with electrical gap junction coupling to reduce large networks of neurons to corresponding representative networks that are more tractable to analysis. The FN model, a two-dimensional simplification of the Hodgkin-Huxley equations for neuronal membrane potential dynamics, exhibits input-dependent regimes of dynamical behavior. In the reduced network, we explore the contributions of external input heterogeneity and coupling strength to determine whether oscillators in the network are firing, quiescent, or saturated. We use the relationships between external input distribution and oscillator states in the reduced network to elucidate properties of oscillators in the original network. Complex behavior in the reduced network includes the presence of mixed mode oscillations and asymptotically periodic behavior. Extensions of these results could be used to inform system identification in complex networked oscillatory systems.

Elizabeth Davison
Princeton University
end@princeton.edu

Biswadip Dey
Princeton University
Department of Mechanical and Aerospace Engineering
biswadip@princeton.edu

Zahra Aminzare, Naomi E. Leonard
Princeton University
aminzare@princeton.edu, naomi@princeton.edu

MS146

Molecular Mechanisms Underlying the Kuramoto Model of Coupled Oscillators

The Kuramoto model has been widely used to describe the synchronizations of a large set of coupled oscillators. In particular, the Kuramto model successfully captures the key features of synchronization of 20,000 coupled cellular rhythms in the circadian clocks of our brain. However, due to the abstractness of the Kuramoto model, specific molecular mechanisms underlying the sinusoidal coupling terms have not been identified. In this talk, I will discuss that the combination of intracellular transcriptional repression mechanisms and intercellular coupling mechanisms in the mammalian circadian clocks can lead to such sinusoidal coupling.

Jae Kyoung Kim
Department of Mathematical Sciences
Korea Advanced Institute of Science and Technology (KAIST)
jaekkim@kaist.ac.kr

Zachary P. Kilpatrick
Department of Applied Mathematics
526 UCB, University of Colorado, Boulder, CO, 80309
USA
zpkilpat@colorado.edu

Matthew Bennett
Rice University
matthew.bennett@rice.edu

Kresimir Josic
University of Houston
Department of Mathematics
josic@math.uh.edu

MS146

Approximating Consensus with Graph Limits

The consensus problem in multi-agent systems has long been the subject of intense research within the fields of computer science and mathematics. This problem can naturally be expressed as a dynamical system such that the interaction between agents is defined by a network. This talk will provide sufficient conditions for when graph limits can be used as a continuum-approximation for the consensus problem on large networks. I will also highlight other aspects of graph limit theory which have implications for the consensus problem.

Barton Lee
School of Mathematics and Statistics
The University of New South Wales
barton.e.lee@gmail.com

MS146

Turing Patterns in Reaction-diffusion Systems on Random Networks

Turing instability in reaction-diffusion systems of activator and inhibitor species leads to formation of non-uniform patterns in continuous media. Turing instability can also take place in reaction-diffusion systems on general networks as pointed out by Othmer and Scriven already in 1971. We consider activator-inhibitor reaction-diffusion systems on large random networks with broad degree distributions and show that the Turing instability leads to non-uniform patterns on networks, in which network nodes differentiate into activator-rich and activator-poor groups. We argue that the backbones of the developed Turing patterns can be understood as bifurcation diagrams of individual network nodes through mean-field approximation of the network Laplacian. We also discuss some related topics, such as pattern formation in bistable reaction-diffusion systems on networks, localization of Laplacian eigenvectors in large random networks with broad degree distributions, and approximation of the system on a network by a system with nonlocal coupling using recent results on graph limits.

Hiroya Nakao
Graduate School of Information Science and Engineering,
Tokyo Institute of Technology
nakao@mei.titech.ac.jp

MS147

Dynamics of Cell Signaling Within a Biofilm

Bacterial cell-cell communication, also termed quorum sensing (QS) is a wide-spread process that coordinates multicellular behaviors such as virulence, biofilm formation, and nutrient acquisition in response to cell density, population structure and environmental viscosity. There has been an explosion in research directed at understanding the molecular mechanisms of QS, but there is a paucity of information on the ecophysiological implications and on the emergent properties of QS regulatory networks. Short circuiting, or self-induction, is a major unanswered question in bacterial QS: How is it that diffusible quorum-signals do not immediately bind to their cognate receptors in the same cell in which they are produced and activate gene expression independent of cell density? We will investigate the roles of antiactivation and lasR regulation in modulating the quorum response and in preventing short-circuiting We will talk about Quorum sensing, Short-Circuiting in Quorum Sensing Systems, and some recent efforts to model some experimental results from the Suel lab on Electrical Communication via Potassium currents within bacterial communities.

Jack D. Dockery
Montana State University
Department of Mathematics
jack.dockery@montana.edu

MS147

Exclusion and Clock Behavior in An Oscillating Chemostat

Microbes form a large and central part of the global ecosystem. As a consequence of their short reproductive time and their proficiency at exchange of genetic material, it seems plausible that microbes in communities operate at high efficiency (in terms of free energy and nutrient usage) in many contexts. One obvious issue of interest would be the description of species within a microbial community and its dependence on the local environment. Description of niche structure of organisms and how that structure impacts competitiveness has long been a topic of interest among ecologists. Here, in the context of Yellowstone National Park microbial mat, we discuss influence of temporal environment on microbial community species structure. The possibilities of competitive exclusion and clocking behavior are discussed.

Isaac Klapper
Temple University
klapper@temple.edu

MS147

Metabolic Processes As Dynamical Systems. A Hotbed of Nonlinear Phenomena?

Abstract Not Available At Time Of Publication.

Doraiswami Ramkrishna
Department of Chemical Engineering
Purdue University
ramkrish@ecn.purdue.edu

MS147

Separating Putative Pathogens from Background Contamination with Principal Orthogonal Decomposition: Evidence for Leptospira in the Ugandan Neonatal Septisome

Neonatal sepsis (NS) is responsible for over 1 million yearly deaths worldwide. Amplicon DNA sequencing can be used to identify organisms that are difficult to detect by routine microbiological methods. However, contaminating bacteria are ubiquitous in hospital settings and research reagents. We sequenced the bacterial 16S rRNA gene obtained from blood and cerebrospinal fluid (CSF) of 80 neonates presenting with NS to the Mbarara Regional Hospital in Uganda. Assuming that patterns of background contamination would be independent of pathogenic microorganism DNA, we applied a novel filtering approach using principal orthogonal decomposition to separate background contamination from potential pathogens in sequencing data. We employed a statistical random matrix bootstrap hypotheses to estimate significance. These analyses demonstrate that Leptospira appears present in some infants presenting within 48 hr of birth, indicative of infection in utero, and up to 28 days of age, suggesting environmental exposure. This organism cannot be cultured in routine bacteriological settings, and is enzootic in the cattle that the rural peoples of western Uganda often live in close proximity. Our computational strategy can reveal putative pathogens in small biomass samples, revealing an important medical finding that has the potential to alter therapy and prevention efforts in a critically ill population.

Steven J. Schiff
Penn State University
Center for Neural Engineering
sschiff@psu.edu

MS148

Multivariate Dependence Beyond Shannon Information

Accurately determining dependency structure is critical to discovering a system's causal organization. We demonstrate that Shannon-like information measures fail at this when used to analyze multivariate dependencies. This has broad implications, particularly when employing information to express the organization and mechanisms embedded in complex systems. Here, we do not suggest that any aspect of information theory is wrong. Rather, the vast majority of its informational measures are simply inadequate for determining the meaningful dependency structure within joint probability distributions. Therefore, such information measures are inadequate for discovering intrinsic causal relations. We close by demonstrating that such distributions exist across an arbitrary set of variables, and discuss several potential avenues toward rectifying this issue.

Ryan G. James
University of California, Davis
rgjames@ucdavis.edu

MS148

Prediction vs Generation in Simple Markov Chains

We present the minimal generators for all binary Markov chains and calculate their generative complexity. While this is in general a non-convex optimization and thus relies on numerics, we find an analytic solution for this particular set of processes. Importantly, processes in this class have a smaller generative complexity than statistical complexity—the minimal memory required by a *predictor* of the process. We then examine other information theoretic properties of these minimal generators, including their crypticity, oracular information, and gauge information, and compare the minimal generators to minimal predictors.

John R. Mahoney
University of California at Davis
jrmahoney@ucdavis.edu

Josh Ruebeck
Carleton College
Northfield, MN
ruebeckj@carleton.edu

Ryan G. James
University of California, Davis
rgjames@ucdavis.edu

MS148

Significance Testing of Information Theoretic Quantities

Information theory has been tremendously successful in defining the relevant quantities, relationships, and bounds that enable engineers to design communication systems that perform near theoretical limits. Recently, information theory is being pushed in a new direction; rather than defining Shannon limits, this "applied" approach to information theory seeks to infer causal relationships from estimates of conditional mutual information. In this application, it is imperative that the significance of these estimates be computed before any inference is made. Surprisingly, almost no work has been done to develop significance tests for information theoretic quantities. In this talk we give an exact test for mutual information, an exact test for Markov order, and a typical realizations test for transfer entropy.

Shawn D. Pethel
U.S. Army RDECOM
shawn.d.pethel.civ@mail.mil

Daniel Hahs
Torch Technologies
Huntsville, AL
daniel.w.hahs.ctr@mail.mil

MS148

Causation Entropy and Pure Inference of Boolean Factors

Understanding the dynamics and functioning of complex systems is one of the most challenging tasks faced in modern science. A central problem to tackle is to accurately and reliable infer the underlying cause-and-effect (i.e., causal) network from observational data, especially when the system consists of a large number of interacting components and the dynamics is intrinsicaly nonlinear. Utilizing our recently developed theory of causation entropy (J. Sun, D. Taylor, and E. M. Bollt, SIAM Journal on Applied Dynamical Systems 14, 73–106, 2015), we devised an efficient computational approach of optimal causation entropy (oCSE) to infer causal networks from data. In particular, we specialize the general approach to infer Boolean networks, which are widely used in the modeling of biological systems. We demonstrate the effectiveness of our approach using both synthetic and experimental data., and discuss open challenges.

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

Erik Bollt
Clarkson University
bolltem@clarkson.edu

MS149

Master Stability Islands for Amplitude Death in Networks of Delay-Coupled Oscillators

This talk presents a master stability function (MSF) approach for analyzing the stability of oscillation death (OD) in networks of delay-coupled oscillators. Unlike the familiar MSFs for instantaneously coupled networks, which typically have a single input encoding for the effects of the eigenvalues of the network Laplacian matrix, for delay-coupled networks we show that such MSFs generally require two additional inputs: the time delay and the coupling strength. To utilize the MSF for predicting the stability of OD of arbitrary networks for a chosen nonlinear system (node dynamics) and coupling function, we introduce the concept of master stability islands (MSIs), which are two-dimensional stability islands of the delay-coupling space together with a third dimension ("altitude") encoding for eigenvalues that result in stable OD. We compute the MSFs and show the corresponding MSIs for several common chaotic systems including the Rössler, the Lorenz, and Chen's system, and found that it is generally possible to achieve OD and that a nonzero time delay is necessary for the stabilization of the OD states.

Stanley R. Huddy
State University of New Paltz
srh@fdu.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

MS149

Controlling Nonlinear Biological Systems Based on Network Structures

Modern biology provides many networks describing regulations between bio-molecules. It is widely believed that dynamics of molecular activities based on such regulatory networks are the origin of biological functions. In this study we present a mathematical theory to provide an important aspect of dynamics from information of regulatory linkages alone. We also present an application of our theory to a real biological network, and experimental results to verify our prediction. In theoretical part, we show that "feedback vertex set" (FVS) of a regulatory network is a set of "determining nodes" of dynamics [Mochizuki, A., Fiedler, B. et al. (2013) J. Theor. Biol., 335, 130-146]. It assures that i) any long-term dynamical behavior of whole system, such as steady states, periodic oscillations or quasi-periodic oscillations, can be identified by measurements of a subset of molecules in the network, and that ii) the subset is determined from the regulatory linkage alone. The theory also claims that iii) dynamical behavior of whole system can be switched from one attractor to others just by controlling dynamics of FVS. In experimental application, we analyzed a gene network including 90 genes, and responsible for cell differentiation in development of ascidian. We identified five genes in minimum FVS of the network. The exhaustive artificial activation/inhibition of five genes showed that the system could be controlled totally just by controlling activities of five genes in FVS.

Atsushi Mochizuki
Riken Mochizuki Laboratory
mochi@riken.jp

MS149

Dynamic Networks and Delay: Communication Delay on Time Varying Networks

Synchronization of coupled systems remains an important focus area for study of networked components. Such systems admit rich dynamical behaviors, where coupling may lead to simplified or complex system as compared uncoupled node dynamics. For example, simple oscillators may yeild a chaotic coupled system; coupled chaotic oscillators may synchronize along a chaotic trajectory; coupling of chaotic oscillators, under certain heterogeneity conditions, may lead to periodic or steady-state behaviors of the coupled system. We previously examined two very distinct types of network communication schemes: The first, which we called a *Moving Neighborhood Network* created a time-varying network where diffusively couple chaotic oscillators may achieve synchronization, even when the network (at any instant) is severely disconnected. In the second, we considered the implications of communication delay in a fixed network of chaotic oscillator and discover that such coupling can "simplify" the chaotic system to phase synchronized limit cycles. Our focus for this talk is to consider the behavior of a coupled system where we allow the network topology to be time-varying, but also specify that communication pathways provide a time-delay structure to the communications. Coupling of chaotic oscillators, we observe (and describe) an interesting interplay between the competing effects of chaotic synchronization and the simplification of trajectories implied by delay coupling.

Joseph Skufca
Clarkson University
jskufca@clarkson.edu

MS149

Patterns in Circular Networks of Excitable Systems with Time Delay

We consider recurrent pulse-coupled networks of excitable elements with delayed connections, which are inspired by biological neural networks. If the delays are tuned appropriately, the network can either stay in the steady resting state or, alternatively, exhibit a desired spiking pattern. It is shown that such a network can be used as a pattern-recognition system. More specifically, the application of the correct pattern as an external input to the network leads to a self-sustained reverberation of the encoded pattern. In terms of the coupling structure, the tolerance and the refractory time of the individual systems, we determine conditions for the uniqueness of the sustained activity, i.e., for the functionality of the network as an unambiguous pattern detector. We point out the relation of the considered systems with cyclic polychronous groups and show how the assumed delay configurations may arise in a self-organized manner when a spike-time dependent plasticity of the connection delays is assumed. As excitable elements, we employ simplistic coincidence detector models as well as Hodgkin-Huxley neuron models. Moreover, the system is implemented experimentally on a Field-Programmable Gate Array (FPGA).

Serhiy Yanchuk
Humboldt University of Berlin
yanchuk@math.tu-berlin.de

Leonhard Lücken
Institute of Transportation Systems, German Aerospace Center
Berlin, Germany
leonhard.luecken@dlr.de

David P. Rosin, Vasco Worlitzer
Technische Universität Berlin
Hardenbergstrae 36, 10623 Berlin, Germany
davidprosin@gmail.com, vasco.m.worlitzer@campus.tu-berlin.de

MS150

Interfacial Dynamics in Biological Systems

Biological pattern formation has been extensively studied using reaction-diffusion models. These models are inherently local, however many biological systems are known to exhibit nonlocality. In this talk we will discuss nonlocal pattern forming mechanisms in the context of bacterial colony formation with an emphasis on arrested fronts. This will lead to a nonlocal framework to understand the interfacial motion in biological systems. We will apply our approach to model the evolution of bacterial colonies that inhibit the growth of genetically identical colonies.

Scott McCalla
Montana State University
scott.mccalla@montana.edu

James von Brecht
California State University, Long Beach
james.vonbrecht@csulb.edu

MS150

The Soft Mode Plays A Role In Defect Persistence In Pattern-Forming Systems

When the surface of a nominally flat binary material is bombarded with a broad, normally incident ion beam, disordered hexagonal arrays of nanodots can form. Defects, such as dislocations in ripple patterns or penta-hepta pairs in hexagonal arrays, limit the utility of patterns produced by ion bombardment. We show that a neutrally stable soft mode can contribute to the persistence over time of defects that form in the early stages of pattern formation. Topological measures of order provide a method for determining if a defect is removed as the pattern evolves.

Patrick Shipman
Department of Mathematics
Colorado State University
shipman@math.colostate.edu

MS150

Spots and Stripes: Vegetation Patterns in Drylands

Reaction-advection-diffusion systems have been developed to model vegetation patterns in arid regions. These vegetation patterns have been observed in satellite images of the surface of the earth, in arid ecosystems all around the world. Different patterns include gaps, stripes and spots. The formation of patterns has been linked to increased aridity (decreased rainfall). The understanding of transitions between different vegetation patterns may result in early warning signals for an upcoming irreversible desertification. In this talk we focus on the stability of striped patterns in two spatial dimensions. On sloped terrain these patterns naturally form for a general class of two-component reaction-advection-diffusion systems. Is the breakup of stiped patterns in spotted patterns a generic next step in the desertification process? We seek to combine analytical and numerical model results with satellite data analysis.

Eric Siero
Leiden University, Mathematical Institute
siero@uni-muenster.de

MS150

Stripe Formation on Zebrafish Fins

Zebrafish (Danio rerio) is a small fish with distinctive black and yellow stripes that form on its body and fins due to the interaction of different pigment cells. Working closely with the biological data, we present an agent-based model for these stripes that explores the interplay of cells and bone rays on the caudal fin. The development of both wild-type and mutated patterns on the body and fins will be discussed, as well as the non-local continuum limit associated with the model.

Alexandria Volkening, Bjorn Sandstede
Division of Applied Mathematics
Brown University
alexandria_volkening@brown.edu,
bjorn_sandstede@brown.edu

MS151

Effective Variables and Interaction Potentials for Coarse Graining of Macromolecular Systems

The complete thermodynamic and kinetic characterization of high dimensional dynamical systems such as large protein complexes still presents significant challenges. Coarse-grained models have long been used as a practical alternative for the characterization of protein mechanisms over long time scales. The theoretical justification for these reduced models relies on the separation of time scales present in macromolecular systems: it appears that the dynamics of a set of slow variables regulates the behavior of the system over long timescales, suggesting that the remaining, much faster, variables could, in principle, be renormalized into the definition of effective interactions between the slower variables. The definition of a coarse-grained model from a finer-grained one requires two main choices: the degrees of freedom to be considered, and the effective energy function regulating their dynamics. Rigorous mathematical procedures are not usually applied to address these questions. We will discuss our recent attempts to use emerging mathematical tools to tackle these points systematically.

Cecilia Clementi
Rice University
cecilia@rice.edu

MS151

Transfer Operator Approximation Using Low-Rank Tensor Decompositions

In this talk, we will present tensor-based reformulations of data-driven methods such as Dynamic Mode Decomposition (DMD) and Extended Dynamic Mode Decomposition (EDMD) for the analysis of complex dynamical systems. Due to the curse of dimensionality, analyzing high-dimensional systems is often infeasible using conventional methods since the amount of memory required to compute and store modes and eigenfunctions grows exponentially with the size of the system. This can be mitigated by exploiting low-rank tensor approximation approaches. We will show how tensor-based methods can be used to approximate the eigenfunctions of transfer operators. The results are illustrated with the aid of simple fluid dynamics and molecular dynamics examples.

Stefan Klus
Freie Universitat Berlin
stefan.klus@fu-berlin.de

MS151

The Coarse Graining of Neural Field Models

In this talk I will report my recent progress about the coarse-graining of neural field models. The fine scale model we study is a class of conductance-based leaky integrate-and-fire (LIF) models. Instead of the common spatial coarse-graining, we use information-theoretic tools to reduce the LIF model to a Markov process about the time evolution of the distributions of (discretized) membrane potentials of excitatory and inhibitory neurons. After this model reduction, we can rigorously study problems like the stochastic stability and the spiking patterns.

Yao Li
University of Massachusetts Amherst
Department of Mathematics and Statistics
yaoli@math.umass.edu

MS151

The Cgdna Coarse Grain Model of the Sequence-Dependent Statistical Mechanics of DNA

I will describe the cgDNA model, its predictions of sequence-dependent DNA persistence lengths, and how to use the maximum entropy principle to estimate coarse grain model parameters from large scale data sets generated in fine grain Molecular Dynamics training set simulations.

John H. Maddocks
EPFL
john.maddocks@epfl.ch

MS152

Physiologic Model Development Using Data Assimilation and Self-Monitoring Data

This talk will address physiologic model development using data assimilation with self-monitoring data and introduce the larger topic of the mini-symposium data driven biomedical dynamics, modeling and data assimilation. In the context of endocrine (e.g., glucose-insulin) modeling I will introduce self-monitoring data and their constraints. I will then discuss how problem context, e.g., clinical versus basic science goals, drive what mathematics and dynamics are important. I will show some results within both of these contexts related to model development and dynamics. I will conclude with a discussion of data assimilation related challenges including identifiability and uncertainty quantification.

David J. Albers
Colombia University
Biomedical Informatics
dja2119@cumc.columbia.edu

MS152

Statistical Framework for Data Assimilation from Single & Multi-Unit Recording to Mean Field Network Models

We have been working to apply Data Assimilation (DA) methods to synchronize mechanistic-based computational models of neural activity to measurements from real brain. In (Sedigh-Sarvestani, 2012) we demonstrated that computational models of the putative sleep-wake regulatory network could be observed through weak, incomplete measurements of the embedded variables using an implementation of an unscented Kalman filter (UKF). We are currently working to apply these methods for model validation, reconstruction and forecasting in real systems - neural recordings from live, freely behaving rats; and for system debugging in neurological disease states where sleep is disrupted.
A major challenge in this work beyond getting reliable brain-stem recordings in freely behaving animals is the statistical and mixed nature of the recordings. The dynamics represented in the models is that of interacting cell groups. The measurements are unit and multi-unit recordings from brain locations where those cell groups are. Unstated is the relationship between the activity - the firing times - of a singe neuron and the cell group from which it comes. More complex is that a single electrode will typically sense activity from multiple neurons from multiple cell groups. I'll address a framework for addressing the linkage from these measures to the model variables.
Sedigh-Sarvestani, et al. (2012). PLoS Computational Biology, 8(11), e1002788.

Bruce J. Gluckman
Penn State Engineering
brucegluckman@psu.edu

MS152

Dynamics and Big Biomedical Data Sets

Observational Health Data Sciences and Informatics (OHDSI) is an interdisciplinary, international collaborative with 160 researchers from 25 countries to improve health by collaboratively generating evidence to answer questions about diagnosis and treatment. Over 600 million patient records have been encoded in the OHDSI format, and each record is a time series on a non-stationary subject with significant measurement error and bias. Answering medical questions depends on dynamics of the physiology, which varies over time (different drugs and medical interventions available as well as patient variation including aging and disease worsening) and over space (i.e., geographic location of the patient, which includes national differences, regional differences, racial differences, etc.). Early studies have used traditional techniques to address variation, such as self-controlled case series and cohort studies, and a map of variation in treatment pathways for chronic disease over time and space has been produced. Current research attempts to account for bias in the data through lagged regression methods.

George Hripcsak
Columbia University
gh13@cumc.columbia.edu

MS152

Competitive Offline Parameter Estimation for Online Data Assimilation in Glucose Dynamics

Data assimilation with computational models of glucose dynamics offers great promise in personalized diabetes interventions and clinical decision making, but carries significant mathematical challenges. We focus here on the challenges of using offline parameter estimation methods to improve real-time, online forecasts. Specifically, we consider a simple ultradian model of glucose-insulin dynamics, perform parameter estimation using Nelder-Mead optimization, Markov Chain Monte Carlo, and unscented Kalman filtering (UKF) methods, and perform glucose state forecasting using a UKF and a simple, unfiltered model. We evaluate the opportunities and trade-offs when passing parameter estimates between offline and online methods using both model selection criteria and a diabetes-specific error metric, and we discuss how these different approaches can be translated into real-time decision support systems.

Matthew Levine
Columbia University
mel2193@cumc.columbia.edu

David J. Albers
Colombia University
Biomedical Informatics
dja2119@cumc.columbia.edu

Andrew Stuart
Computing + Mathematical Sciences
California Institute of Technology
astuart@caltech.edu

George Hripcsak
Department of Bioinfomatics, Columbia University
hripcsak@columbia.edu

MS153

A Variational Lagrangian Formulation for Nonequilibrium Thermodynamics of Continuum Systems

We develop a Lagrangian variational formulation for the nonequilibrium thermodynamics of continuum systems. This variational formulation extends the Hamilton principle to allow the inclusion of irreversible processes in the dynamics. The irreversibility is encoded into a nonlinear nonholonomic constraint given by the expression of entropy production associated to all the irreversible processes involved. The variational formulation is naturally expressed in material representation, while its spatial version is obtained via a nonholonomic Lagrangian reduction by symmetry. The theory is illustrated with the examples of a viscous heat conducting fluid (the Navier-Stokes-Fourier system) and its multicomponent extension including chemical reactions and mass transfer.

Francois Gay-Balmaz
Ecole Normale Superieure
gaybalma@lmd.ens.fr

Hiroaki Yoshimura
Waseday University
yoshimura@waseda.jp

MS153

Interpolation on Symmetric Spaces via the Generalized Polar Decomposition

Abstract Not Available At Time Of Publication.

Melvin Leok
University of California, San Diego
Department of Mathematics
mleok@math.ucsd.edu

MS153

Variational Discretization for Fluid-structure Interactions

Variational integrators for numerical simulations of Lagrangian systems have the advantage of conserving the momenta up to machine precision, independent of the time step. While the theory of variational integrators for mechanical systems is well developed, there are obstacles in direct applications of these integrators to systems involving fluid-structure interactions. In this talk, we derive a variational integrator for a particular type of fluid-structure interactions, namely, simulating the dynamics of a bendable tube conveying ideal fluid that can change its cross-section (collapsible tube). We start by deriving a fully three-dimensional, geometrically exact theory for flexible tubes conveying fluid. Our approach is based on the symmetry-reduced, exact geometric description for elastic rods, coupled with the fluid transport and subject to the volume conservation constraint for the fluid. Using these methods, we obtain the fully three dimensional equations of motion. We then proceed to the linear stability analysis and show that our theory introduces important corrections to previously derived results, both in the consistency at all wavelength and in the effects arising from the dynamical change of the cross-section. Based on this theory, we derive a variational discretization of the dynamics based on the appropriate discretization of the fluids back-to-labels map, coupled with a variational discretization of elastic part of the Lagrangian.

Vakhtang Putkaradze
University of Alberta
putkarad@ualberta.ca

MS153

Explicit High-Order Symplectic Integration of Arbitrary Hamiltonians

Symplectic integrators preserve the phase-space volume and have favorable performances in long time simulations. Methods for explicit symplectic integration have been extensively studied for separable Hamiltonians (i.e., H(q,p)=K(p)+V(q)), and they lead to both accuracy and efficiency. However, nonseparable Hamiltonians also model important problems. Unfortunately, implicit methods had been the only available symplectic approach with long-time accuracy for general nonseparable systems. This talk will construct high-order symplectic integrators for nonseparable systems that use explicit updates. These new integrators are based on a mechanical restraint that binds two copies of phase space together. Using backward error analysis, KAM theory, and some additional multiscale analysis, a pleasant error bound is established for integrable systems. Numerical evidence of statistical accuracy for non-integrable systems were also observed.

Molei Tao
School of Mathematics, Georgia Institute of Technology
mtao@gatech.edu

MS154

Modulational Stability of Quasiperiodic Solutions to Hamiltonian PDEs

We consider the stability of quasi-periodic solutions to nonlinear dispersive PDEs. We construct a rigorous Whitham theory giving stability information about the quasiperiodic solutions in terms of conserved quantities of the evolution evaluated along the manifold of quasiperiodic solutions. This is joint work with Robert Marangell and Mat Johnson.

Jared Bronski
University of Illinois Urbana-Champaign
Department of Mathematics

jared@math.uiuc.edu

MS154

Application of the Maslov Index to the Stability of Traveling Waves

This talk concerns the stability of fast traveling waves for the doubly diffusive FitzHugh-Nagumo equation. The traveling wave system admits a symplectic structure, which helps to determine the unstable spectrum for the linear operator L arising from linearizing about the wave. Using a topological invariant called the Maslov index, it is shown that there are no eigenvalues for L in the right-half plane, and hence the wave is stable. The calculation of the Maslov index (which is often elusive) is facilitated by the presence of multiple timescales in the equations.

Paul Cornwell
Department of mathematics
University of North Carolina at Chapel Hill
pcorn@live.unc.edu

Chris Jones
University of North Carolina-Chapel Hill
ckrtj@email.unc.edu

MS154

Computation and Stability of Patterns in Second Order Evolution Equations

In this talk we consider nonlinear traveling waves occurring in systems of semilinear damped wave equations. A numerical method which proves to be very useful for the numerical approximation of traveling waves and also more general relative equilibria in evolution equations is the freezing method. We show how the method generalizes to second order evolution equations. The method introduces the waves velocity as a new unknown and transforms the original PDE into a partial differential algebraic equation (PDAE). Provided the traveling wave of the original PDE has suitable stability properties, we will present a rigorous theory which shows the main benefit of the freezing method: By solving the Cauchy problem for the PDAE reformulation, not only a solution to the original PDE is obtained but also a co-moving frame is generated in which the solution becomes stationary. Moreover, the additional unknown converges to the velocity of the traveling wave. Numerical examples demonstrate our analytical findings.

Wolf-Juergen Beyn, Denny Otten
Bielefeld University
beyn@math.uni-bielefeld.de, dotten@math.uni-bielefeld.de

Jens Rottmann-Matthes
Department of Mathematics
Karlsruhe Institute of Technology
jens.rottmann-matthes@kit.edu

MS154

Stability of Nozaki-Bekki Holes Near the Nonlinear Schrdinger Limit

The Nozaki-Bekki holes are source defects in the cubic Ginzburg-Landau equation: they are degenerate in the sense that they come in a one-parameter family instead of a discrete family. Their stability properties for the underlying PDE are not well understood. In this talk, I will discuss results about their spectral stability in the limit of the nonlinear Schrodinger equations. In contrast to earlier work, which indicated that there are three eigenvalues near the origin, we prove that an appropriate Evans function has six roots near the origin. I will elucidate the underlying geometry and highlight consequences for the stability of the Nozaki-Bekki holes for the cubic-quintic Ginzburg-Landau equation.

Margaret Beck
Boston University
mabeck@math.bu.edu

Toan Nguyen
Pennsylvania State University
nguyen@math.psu.edu

Bjorn Sandstede
Division of Applied Mathematics
Brown University
bjorn_sandstede@brown.edu

Kevin Zumbrun
Indiana University
USA
kzumbrun@indiana.edu

MS155

Unexpected Patterns: Chimera States on Networks

When identical oscillators are coupled together in a network, dynamical steady states are often assumed to reflect network symmetries. I'll show evidence for the existence of alternative persistent states that break the symmetries of the underlying coupling network. These symmetry-broken coexistent states are analogous to those dubbed "chimera states," which can occur when identical oscillators are coupled to one another in identical ways.

Daniel M. Abrams
Northwestern University
dmabrams@northwestern.edu

MS155

Synchronization in Lattices of Interacting Quantum Dipoles

Arrays of synchronized oscillators are ubiquitous in biological, physical and engineering systems. In this talk I will discuss the emergence of synchronization in arrays of quantum radiating dipoles coupled only via anisotropic and long-range dipolar interactions. We find that in the presence of an incoherent energy source, dipolar interactions can lead to a resilient synchronized steady-state. A classical mean-field description of the model results in equations similar to the classical Kuramoto model for synchronization of phase oscillators. Using the mean-field formulation for the all-to-all coupled case, we study the synchronized state and find that it exists only for a finite range of the external energy source rates. We compare the results obtained from the mean-field model with numerical simulations of the quantum system and find that synchronization is robust to quantum fluctuations and spatially decaying coupling. The robustness of additional nonstationary synchronization patterns to more accurate descriptions of the quantum system is discussed.

Juan G. Restrepo
Department of Applied Mathematics

University of Colorado at Boulder
Juanga@Colorado.EDU

MS155

Control and Optimization of Phase and Chaotic Oscillator Networks

Controlling and optimizing synchronization is vital is applications ranging from the power grid to synthetic cell engineering. In this talk we will explore both control and optimization in the context of phase oscillators and chaotic oscillators, respectively. First, we present a new nonlinear dynamics-based method for controlling coupled phase oscillator networks with minimal intervention by identifying a target synchronized state and using its Jacobian to determine which oscillators require control. We also extend these results to networks of limit-cycle oscillators and explore various control strategies. Second, we consider the optimization of networks of heterogeneous chaotic oscillators. In particular, we apply the framework of the synchrony alignment function - a recently developed technique for optimizing synchronization in networks of phase oscillators - to this more complicated case. Using both numerical simulations and an experimental setup we demonstrate that this framework performs remarkably well.

Per Sebastian Skardal
Trinity College
Department of Mathematics
persebastian.skardal@trincoll.edu

MS155

Optimal Synchronization of Complex Networks

Synchronization is central to many complex systems in engineering physics (e.g., the power grid, Josephson junction circuits, and electrochemical oscillators) and biology (e.g., neuronal, circadian, and cardiac rhythms). Despite these widespread applications, for which proper functionality depends sensitively on the extent of synchronization, there remains a lack of understanding for how systems can best evolve and adapt to enhance or inhibit synchronization. We study how network modifications affect the synchronization properties of network-coupled dynamical systems that have heterogeneous node dynamics (e.g., phase oscillators with nonidentical frequencies), which is often the case for real-world systems. Our approach relies on a synchrony alignment function (SAF) that quantifies the interplay between heterogeneity of the network and of the oscillators and provides an objective measure for a system's ability to synchronize. We conduct a spectral perturbation analysis of the SAF for structural network modifications including the addition and removal of edges, which subsequently ranks the edges according to their importance to synchronization. Based on this analysis, we develop gradient-descent algorithms to efficiently solve optimization problems that aim to maximize phase synchronization via network modifications.

Dane Taylor
Department of Mathematics
University of North Carolina at Chapel Hill
dane.r.taylor@gmail.com

Per Sebastian Skardal
Trinity College
Department of Mathematics
persebastian.skardal@trincoll.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

MS156

Analysis of Freeway Traffic Using Koopman Operator Methods

Over the years, there have been various types of mathematical models proposed within the field of traffic physics, all with varying degrees of success. The goal of this talk is to demonstrate how the Koopman operator theory framework can offer a model-free, data-driven method for accurately capturing and predicting traffic dynamics. The effectiveness of the proposed framework is demonstrated by an application to the Next Generation Simulation (NGSIM) data set collected by the US Federal Highway Administration. The NGSIM data set provides individual vehicle trajectory data for a segment of the US 101 and US 80 Highways. By obtaining a Koopman mode decomposition of the observed data sets, we are able to accurately reconstruct our observed dynamics, distinguish any growing or decaying modes, and reconstruct a hierarchy of coherent spatiotemporal patterns that are fundamental to the observed dynamics. Furthermore, the proposed method can be utilized to predict traffic dynamics by obtaining a decomposition of a subset of the data, that is then used to predict a future subset of the data.

Allan Avila
University of California, Santa Barbara
aavil016@ucr.edu

MS156

Koopman Operators for Reduced Order Modeling of Nonlinear Dynamical Systems

Abstract Not Available At Time Of Publication.

Karthik Duraisamy
University of Michigan Ann Arbor
kdur@umich.edu

MS156

Koopman Theory, Observables and Sparse Regression for PDE's

We consider the application of Koopman theory to nonlinear partial differential equations. We demonstrate that the observables chosen for constructing the Koopman operator are critical for enabling an accurate approximation to the nonlinear dynamics. If such observables can be found, then the dynamic mode decomposition algorithm can be enacted to compute a finite-dimensional approximation of the Koopman operator, including its eigenfunctions, eigenvalues and Koopman modes. Judiciously chosen observables lead to physically interpretable spatio-temporal features of the complex system under consideration and provide a connection to manifold learning methods. We demonstrate the impact of observable selection, including kernel methods, and construction of the Koopman operator on two canonical, nonlinear PDEs: Burgers' equation and the nonlinear Schrödinger equation. These examples serve to highlight the most pressing and critical challenge of Koopman theory: a principled way to select appropriate observables.

Nathan Kutz

University of Washington
Dept of Applied Mathematics
kutz@uw.edu

MS156

Baroreflex Physiology Using Koopman Mode Analysis

We propose new methods for the evaluation of eigenvalues $\lambda^{(t,t_0)}$ of the Koopman operator family $\mathcal{K}^{(t,t_0)}$, $t > t_0$ of the non-autonomous dynamic systems. The first step in the development is a new data-driven method for very accurate evaluation of eigenvalues $\lambda^{(t,t_0)}$, $t > t_0$ in the hybrid linear non-autonomous case. Then, the approach is extended to continuous linear non-autonomous systems and non-autonomous systems in general. We also propose a relationship between eigenvalues $\lambda^{(t,t_0)}$, $t > t_0$ and eigenvalues computed by Arnoldi-like methods on large sets of snapshots. We apply the new approach to baroreflex physiology, i.e. to the resonant breathing which is used in PTSD treatment. For the resonant breathing we have both data and parameterized mathematical model. The model incorporates a delay and thus is infinite dimensional, hybrid, with a stochastic input. Its asymptotic dynamics is close to quasi-periodic. The applied new methods give an improved insight to the eigenvalues of the related Koopman operator family $\mathcal{K}^{(t,t_0)}$.

Senka Macesic
University of Rijeka, Croatia
senka.macesic@riteh.hr

Igor Mezic
University of California, Santa Barbara
mezic@engineering.ucsb.edu

Maria Fonoberova
AIMdyn, Inc
mfonoberova@aimdyn.com

Nelida Crnjaric-Zic
Rijeka University
nelida@riteh.hr

Zlatko Drmac
University of Zagreb
Department of Mathematics
drmac@math.hr

Aleksandr Andrejcuk
University of Rijeka, Croatia
aleksandr.andrejcuk@gmail.com

MS157

Dual-Mechanism Firing Rate Homeostasis Stabilizes Multiple Firing Rate Statistics

Homeostatic processes that provide negative feedback to regulate neuronal firing rates are essential for normal brain function. Indeed, multiple parameters of individual neurons, including the scale of afferent synapse strengths and the densities of specific ion channels, have been observed to change on homeostatic time scales in response to chronic changes in synaptic input. This raises the question of whether these processes are controlled by a single slow feedback variable or multiple slow variables. A single homeostatic process providing negative feedback to a neuron's firing rate naturally maintains a stable homeostatic equilibrium with a characteristic mean firing rate; but the conditions under which multiple slow feedbacks produce a stable homeostatic equilibrium have not yet been explored. We consider a highly general model of homeostatic firing rate control in which two slow variables provide negative feedback to drive a firing rate towards two different targets. Using dynamical systems techniques, we show that such a control system can stably maintain a neuron's characteristic firing rate mean and variance in the face of perturbations, and we derive conditions under which this happens. We also derive expressions that clarify the relationship between the homeostatic firing rate targets and the resulting stable firing rate mean and variance. We show that one role that dual homeostasis can serve is to tune a neuronal network to act as an integrator.

Jonathan Cannon
Brandeis University
theoceanistea@gmail.com

MS157

Feedback, Singularities and Singular Perturbations in Robust Neuromodulation

Neurons are excitable cells whose electrical activity ultimately determine how information is processed through the brain. In our complex and changing environment, animals need to constantly switch between different behavioral states. The most striking and evident changes probably occur at the sleep-wake transitions, and effective neural control of these transitions is critical for the fitness and survival of the animal. These behavioral switches are accompanied by changes in neural activity patterns in many brain areas. A grand challenge of neuroscience is to understand how those changes are robustly attained via a plethora of neuromodulators and despite large variability at the network, cell, and molecular levels. This talk will introduce a mathematical framework to tackle this challenge in a constructive way via the joint use of feedback, singularity, and singular perturbation theories. Feedback theory maps neuron electrophysiology to multiple timescale feedback motifs that capture the qualitative features of neuronal dynamics. Those motifs are rigorously dissected via singularity and singular perturbation theories to formulate predictions about the possible activity modes robustly observable in neuronal dynamics and the mechanisms underlying switches between different modes. These theoretical predictions are qualitatively mapped back to electrophysiology to formulate experimentally relevant predictions about the mechanisms underlying robust neuromodulation.

Alessio Franci
Universidad Nacional Autónoma de México
México
afranci@ciencias.unam.mx

Guillaume Drion
Neurophysiology Unit and GIGA Neurosciences
University of Liege, Liege, Belgium
gdrion@ulg.ac.be

Rodolphe Sepulchre
University of Cambridge
Cambridge, UK
r.sepulchre@eng.cam.ac.uk

MS157

Model Formulation and Experimental Challenges

in Underactuated Neurocontrol

Despite recent technological advances, neurostimulation applications typically fall within one of two extremes of scale: controlling precise spike patterns in small numbers of neurons, or driving large ensembles using bulk perturbation, such as in deep brain stimulation. However, most theories of neural coding, e.g. in sensory systems, exist at an intermediate scale, where neuron identity carries information, but overall function arises from large ensembles (e.g. $\sim 10^4$ neurons in a cortical column). An essential challenge is thus development of neurostimulation strategies at this intermediate scale: independent control of large numbers of 'individual' neurons. I will describe our efforts towards bridging control theory with *in vivo* neurophysiology. We focus on underactuated control objectives, where the ratio of neurons to stimulation channels can be $> 100 : 1$. We exploit neural heterogeneity to design controls for ensembles that are naively uncontrollable. We argue that robustness may motivate intentional model misspecification. In mouse somatosensory cortex recordings, we have begun estimating parameter heterogeneity as applied to control design, as distinct from accurate biophysical descriptions. Early results suggest a distribution of parameters qualitatively consistent with our model assumptions. Taken together, these results are step towards a unified systems-theoretic framework for optimal control of dynamics in large neuronal networks.

Jason Ritt
Massachusetts Institute of Technology
MIT E25-436
jritt@bu.edu

Anirban Nandi
Washington University, St. Louis
anirban.nandi@wustl.edu

ShiNung Ching
Washington University in St. Louis
shinung@ese.wustl.edu

MS157

Folded Saddle Nodes: Understanding Transitions Between Activity Patterns in a Coupled Neuron Model

The Butera model is a well known model of two synaptically coupled neurons in a region of the brain stem known as the pre-Botzinger complex, which play a part in generating breathing rhythms in mammals. In this talk, we will discuss the bifurcations corresponding to the transitions between various bursting and spiking states of the model. In particular, we will investigate a new type of folded saddle-node bifurcation (FSN III) which arises in the context of slow-fast averaging.

Kerry-Lyn Roberts
The University of Sidney
K.Roberts@maths.usyd.edu.au

MS158

Local and Global Optimization of Particle Locations on the Sphere: Models, Applications, Mathematical Aspects, and Computations

Ordered arrangements of particles on the boundary of a domain in two or three dimensions, with potential interaction forces depending on pairwise distances, arise in multiple applications. For N identical particles, even in simplest geometries, such as the sphere in 3D, the computation of optimal designs that minimize the global energy is a challenging problem. When $N \gg 1$, the situation is further complicated by the rapid growth of local minimum numbers. The case of nonidentical particles adds further complexity. As a result, only putative optimal spherical designs of $N \gg 1$ particles are known from global optimization, even for basic potentials. Mathematical proofs of optimality of certain arrangements for certain potentials are known only for highly symmetric cases. Questions like universal optimality (existence of a design minimizing a class of energies) generally remain open. In this talk, we present an algorithm for the computation of N-particle arrangements on a unit sphere corresponding to local and putative global energy minima, for a given pairwise potential. Geometrical properties, such as pairwise distances and coordination numbers, are used to characterize, quantify, and distinguish between particle arrangements. Putative globally and locally optimal configurations obtained for several different pairwise energies, and their properties, are discussed. A companion talk by W. Ridgway focuses on the global-local optimization numerical algorithm.

Alexei F. Cheviakov
Department of Mathematics and Statistics
University of Saskatchewan
cheviakov@math.usask.ca

MS158

Mean First Passage Time with Space-dependent Diffusion

We consider the problem of having many traps inside a bounded domain where the particle velocity is non-uniform (space-dependent). We ask the following question: how should the traps be distributed to optimally trap a randomly moving particle? In the limit of many traps, a mean-field description yields some surprising answers.

Theodore Kolokolnikov
Dalhousie University
tkolokol@mathstat.dal.ca

MS158

Boundary Homogenization of a Spherical Target and Berg-Purcell Revisited

We consider the classic chemoreception problem of capture by a structured spherical target with a distribution of small absorbing surface traps. In now seminal work, physicists Berg and Purcell postulated in 1977 an expression for the capture rate of such a target. From a flux based analysis, they determined that the capture rate should depend on the combined perimeter of the absorbers. Therefore, for a fixed absorbing area, a highly fragmented distribution leads to a nearly optimal capture flux compared to an all absorbing target. In this work, we give a first principles derivation of the classic Berg and Purcell result and also determine its higher order corrections which give detailed information on the spatial configuration of the absorbing locations. The result is derived in the limit of small absorber radius and gives an explicit discrete intertrap interaction energy. This high order expansion is used to homogenize the boundary of the target and determine an effective Robin boundary condition for the target in the limit of large trap numbers. Our theoretical results are verified with a spectral boundary element method.

Alan E. Lindsay
Applied Computational Mathematics and Statistics
University of Notre Dame
a.lindsay@nd.edu

Michael Ward
Department of Mathematics
University of British Columbia
ward@math.ubc.ca

Andrew J. Bernoff
Harvey Mudd College
Department of Mathematics
ajb@hmc.edu

MS158

Numerical Computation of Locally and Globally Energy-Minimizing Spherical Designs

Multiple applications, including ones in material science, solid state physics, and cell biology, involve ordered arrangements of particles on the surface of a sphere. Basic examples include trap arrangements in the narrow escape problem for a Brownian particle in biophysics, and the study of surface defects in spherical crystals. In many situations, the ordered arrangements are local or global minima of a pairwise potential energy. A systematic search of energy-minimizing configurations, even for a simple pairwise potential and identical particles on the sphere, presents a challenging computational problem. In this talk we present an efficient optimization algorithm for the computation of N-particle energy minima from known $(N-1)$-particle energy minima. We discuss the implementation of local and global optimization, exclusion of saddle points, convergence properties, and other aspects of the algorithm. Results are presented for different choices of the pairwise potential energy function. This is a joint work with Alexei Cheviakov.

Wesley J. Ridgway
Department of Mathematics.
University of Saskatchewan
wjr704@mail.usask.ca

MS159

Nonlinear Stochastic Models for Irregular Time Series: Empirical Model Reduction and Multilayer Stochastic Models

We derive stable and efficient data-based models for simulation and prediction in the sciences (Kondrashov et al., Physica D, 2015). The proposed low-order models use a multivariate time series of partial observations from a large-dimensional system; they are compared with the optimal closures provided by the Mori-Zwanzig (MZ) formalism of statistical physics. Our multilayer stochastic models (MSMs) generalize existing multilevel, regression-based approaches to data-based closure, in particular empirical model reduction (EMR). We show that the MSMs' multilayer structure can provide a natural Markov approximation to the generalized Langevin equation (GLE) of the MZ formalism. A simple criterion for an EMR-MSM model is derived to assess how well it approximates the GLE solution. Sufficient conditions are given to guarantee the existence of a global random attractor for a given MSM. This existence ensures that no blow-up can occur for a very broad class of MSM applications. We confirm the absence of blow-up and the faithful reproduction of the main statistical properties of the full, high-dimensional model by an EMR-MSM in two illustrative cases: (i) a conceptual, nonlinear, stochastic climate model of coupled slow and fast variables, in which only slow variables are observed; and (ii) a partially observed, generalized Lotka-Volterra model of population dynamics in its chaotic regime.

Michael Ghil
Ecole Normale Superieure, Paris, and
University of California, Los Angeles
ghil@lmd.ens.fr

Mickael Chekroun
University of California, Los Angeles
Department of Atmospheric and Oceanic Sciences
mchekroun@atmos.ucla.edu

Dmitri Kondrashov, Andreas Groth
Department of Atmospheric and Oceanic Sciences
University of California, Los Angeles
dkondras@atmos.ucla.edu, andreasgroth@ucla.edu

MS159

Representing Time Series with Uncertainties and Identification of Abrupt Transitions

We put forward a novel representation for observed time series: in lieu of considering measurements as a point-like estimate with concomitant error, we propose to consider them as a sequence of time-ordered probability densities. In our framework, uncertainties of the datasets—arising either from spatial or temporal variations, or from measurement imprecision—are inherently quantified from the beginning of the analysis and are carried over throughout subsequent analyses of the data as well. We show how a matrix of recurrence probabilities can be estimated analytically from such a sequence of time-ordered probability densities, and how such a measure of the recurrences of the system can then be used to infer sudden dynamical changes in the dataset. We demonstrate our approach with three kinds of real-world examples: paleoclimatic data, historic climatic data, and financial data. Our results capture several well-known paleoclimatic and historic climatic events, and well-known financial crashes, while also revealing several other events in the data which are understood to a lesser degree.

Bedartha Goswami
Potsdam Institute for Climate Impact Research
Potsdam Institute for Climate Impact Research
goswami@pik-potsdam.de

Aljoscha Rheinwalt
Institute for Earth and Environmental Science
University of Potsdam
rheinwalt@uni-potsdam.de

Niklas Boers
Laboratoire de Meteorologie Dynamique
Ecole Normale Superieure, Paris
boers@pik-potsdam.de

Norbert Marwan, Jobst Heitzig
Potsdam Institute for Climate Impact Research
marwan@pik-potsdam.de, heitzig@pik-potsdam.de

Sebastian Breitenbach
Institute of Geology, Mineralogy & Geophysics

Ruhr-Universitaet Bochum
sebastian.breitenbach@rub.de

Juergen Kurths
Potsdam Institute for Climate Impact Research
kurths@pik-potsdam.de

MS159

Determining the Kolmogorov-Sinai Entropy from Ordinal Patterns

Quantifying the complexity of a time series is an important subject of research, especially if this helps distinguishing deterministic chaotic signals from stochastic ones. The Kolmogorov-Sinai entropy is, in principle, the right indicator to look at, but obtaining reliable estimates is quite problematic even in the case of relatively low-dimensional chaos. I show that a relevant step forward can be made, by combining the analysis of ordinal patterns with the measurement of the width of the corresponding cylinder sets. Many years ago, Bandt and Pompe suggested to encode finite sequences of data as ordinal patterns, by assigning at each datum within a given window its relative order (largest, second largest, and so on). The corresponding entropy, called permutation entropy, is often used as a proxy for the Kolmogorov-Sinay entropy. However, even in the simple, one-dimensional, logistic map, strong deviations are found between the two quantities for the numerically accessible window lengths. I propose to look at the dispersion among all trajectories characterised by the same ordinal pattern: a suitably modified "relative" permutation entropy, which takes this information into account allows for by far much more accurate estimates even in dynamical systems with multiple positive Lyapunov exponents. The method is illustrated by discussing a few different models, of increasing complexity.

Antonio Politi
University of Aberdeen, UK
a.politi@abdn.ac.uk

MS159

From Symbolic Dynamics to Ordinal Partition Networks: Constructing Proxies of the Dynamical System from Observed Time Series

We consider methods to extract features of a dynamical system $\Phi : \mathcal{M} \to \mathcal{M}$ observed via a instantaneous scalar measurement function $h : \mathcal{M} \to \mathbf{R}$. Of course, the gold-standard of such methods is delay reconstruction via an invocation of Takens' embedding theorem. However, such approaches are severely challenged by finite data observational and dynamical noise, and excessively large sampling interval. Instead, we focus on a class of methods that reconstruct a network representation of the underlying dynamical system via and ordinal encoding of successive observed time series points. That is, for a chosen window size w, we replace the observations $(x_t, x_{t+\tau}, \dots, x_{t+(w-1)\tau})$ with a permutation of the integers $1, 2, 3, \dots, w$ which reflects the order of the original points. In this talk we will describe why this is a good thing to do, both theoretically, and from the pragmatic objective of application. We will demonstrate the efficacy of the approach and introduce new extensions of the method to the situation where the permutation window size w may be variable. To do this, we consider the permutation windows as code words and apply standard encoding schemes to construct efficient and complete codes for the sequence of amplitude orderings.

Michael Small
The University of Western
Australia - WSA
michael.small@uwa.edu.au

Michael McCullough, Konstantinos Sakellariou, Thomas Stemler, David Walker
University of Western Australia
michael.mccullough@research.uwa.edu.au, konstantinos.sakellariou@research.uwa.edu.au,
thomas.stemler@uwa.edu.au, david.walker@uwa.edu.au

MS160

Assessing the Contribution of Distinct Vascular Segments in Peripheral Arterial Disease

Peripheral arterial disease (PAD) is a major health problem in which systemic arteries become occluded, leading to a significant reduction in blood supply to tissue. There is an ongoing controversy regarding the potential efficacy of PAD therapies that rely on new vessel formation versus the dilation of existing vessels to restore tissue perfusion. The theoretical model presented here provides a method for resolving this controversy by identifying the relative contributions of short- (acute) and long-term (chronic) vascular adaptations to the collateral arteries and distal microvasculature following a major arterial occlusion. A computational hemodynamic model analogous to an electrical circuit is developed in which vessel compartments are defined as resistors connected in both series and parallel according to the observed network geometry of the rat hindlimb. The model is used to test the sensitivity of blood flow to changes in vessel number or diameter following an abrupt, total, and sustained femoral arterial occlusion. The model shows that an occlusion shifts the site of primary vascular resistance from arterioles to collateral arteries and that new vessel formation independent of collateral growth has little to no effect on restoring tissue perfusion. The model is also used to predict the degree of collateral dilation required to achieve experimentally observed flow values in the rat hindlimb following an occlusion under rest and exercise conditions.

Julia Arciero
Department of Mathematical Sciences
Indiana University-Purdue University Indianapolis
jarciero@math.iupui.edu

MS160

Modeling, Analysis, and Experiment Design for Syk-Mediated Signalling Events in B Cells

B cells play an important role in immune system response and are activated by a complex chain of signalling events, either with or without mediation by T cells. Depending on the level and type of binding events associated with a B cell, it may develop in one of several ways; understanding the mechanism behind the associated activation or inactivation is an important component of understanding immune response more generally. The kinase Syk plays a central role in early signaling events in B cells and is required for proper response when antigens bind to B cell receptors (BCRs). Experiments using an analog-sensitive version of Syk (Syk-AQL) have better elucidated its role, but have not completely characterized its behavior. We present a computational model for BCR signaling, using dynamical systems, which incorporates both wild-type Syk and Syk-

AQL. Following the use of sensitivity analysis to identify significant reaction parameters, we screen for parameter vectors that produce graded responses to BCR stimulation as is observed experimentally. We demonstrate qualitative agreement between the model and dose response data for both mutant and wild-type kinases. The model provides suggestions for how manipulation of Syk-AQL can be used to modulate the downstream response associated with BCR stimulation.

Reginald Mcgee
The Ohio State University
mcgee.278@mbi.osu.edu

Gregery Buzzard
Purdue University
buzzard@purdue.edu

MS160

Multi-scale Model of Breast Cancer Predicts Response to Anti-angiogenic Therapies

Angiogenesis, the formation of new blood capillaries from pre-existing vessels, is a hallmark of cancer. Thus far, strategies for reducing tumor angiogenesis have focused on inhibiting pro-angiogenic factors, while less is known about the therapeutic effects of mimicking the actions of angiogenesis inhibitors. Thrombospondin-1 (TSP1) is an important endogenous inhibitor of angiogenesis that has been investigated as an anti-angiogenic agent. TSP1 impedes the growth of new blood vessels in many ways, including crosstalk with potent pro-angiogenic factors such as vascular endothelial growth factor (VEGF). Given the complexity of TSP1 signaling, a predictive systems biology model would provide quantitative understanding of the angiogenic balance in tumor tissue. Therefore, we have developed a molecular detailed model of interactions between TSP1 and VEGF. The model predicts the distribution of the angiogenic factors in tumor tissue and throughout the body, providing insight into the angiogenic balance (and its disruption) in cancer. We utilize the model to simulate administration of exogenous TSP1 mimetics, alone and in combination with VEGF-targeting agents. The model predicts the ratio of receptor-bound VEGF to receptor-bound TSP1 under various tumor microenvironmental conditions, identifying the ideal tumor profile that responds to these therapeutic strategies. Our model provides a quantitative framework to study the effects of anti-angiogenic treatment.

Stacey Finley
Johns Hopkins University
Department of Biomedical Engineering
sfinley@usc.edu

MS160

Dynamic Modeling of Tuberculosis Granuloma Activation

Tuberculosis (TB) is one of the deadliest infectious diseases. TB is spread by inhaling Mycobacterium tuberculosis. The bacteria are attacked by the immune system in the lungs. Aveolar macrophages cluster the bacteria into cellular aggregates called granulomas. Granulomas can contain the bacteria in a dormant state for long periods of time, even decades, in a condition called latent TB. However, the bacteria persist and can be activated when the granulomas are compromised by other immune response events in a host, such as cancer, HIV, or aging. The activation and subsequent spread of bacteria leads to active TB disease. It is difficult to study the activation process in humans because those with latent TB are asymptomatic and are often undiagnosed. Current animal models all have limitations. Several previous mathematical models describe the infection or granuloma formation stages of TB. No approach considers the dynamics of matrix metalloproteinase 1 (MMP-1) regulation and its impact on TB activation. MMP-1 dysregulation has been implicated in TB activation experimentally, but the mechanism is not well understood. The overall objective of the study is to predict TB activation dynamics in response to MMP-1 dysregulation. We will discuss a mathematical model to test the hypothesis that the dynamics of MMP-1 regulation play a key role in the transition from latent TB to active TB.

Steven Ruggiero, Minu Pilvankar, Ashlee N. Ford Versypt
Oklahoma State University
steve.ruggiero@okstate.edu, minu.pilvankar@okstate.edu, ashleefv@okstate.edu

MS161

Subdiffusion with Reactions and Forces

The mathematics of subdiffusion has been well developed over the past two decades with the governing equations obtained from continuous time random walks, stochastic modelling and fractional calculus. In this talk I will go through a derivation of the generalized master equation, including the diffusion limits, for an ensemble of particles undergoing reactions and subject to external forces, in a subdiffusive environment. I will also show how the model equations can be solved numerically by revisiting the diffusion limit equations through a discrete time random walk formalism. Some open problems and future directions will also be discussed.

Christopher N. Angstmann
UNSW Australia
c.angstmann@unsw.edu.au

Bruce I. Henry
School of Mathematics and Statistics
University of New South Wales
B.Henry@unsw.edu.au

MS161

Slow Subdiffusion-Reaction Equation

We will consider the slow-subdiffusion process with reactions of type $A + B \to B$ in which particles A are assumed to be static whereas B are assumed to be mobile. Slow subdiffusion occurs when the Laplace transform of function $\omega(t)$ is a slowly varying function. The function $\omega(t)$ is a probability distribution of time which is needed for a particle to take its next step. Starting with the difference equation, which describes a random walk of particle in a system with reactions, using the generating function method and the continuous-time random walk formalism, we will derive the slow-subdiffusion equation. We will find its solution (Green's function) over a long time limit. Difference between the Green's function which describes 'standard' subdiffusion with reactions and the Green's function which describes slow subdiffusion with reactions will also be discussed.

Tadeusz Kosztolowicz
Institute of Physics, Jan Kochanowski University

tadeusz.kosztolowicz@ujk.kielce.pl

MS161

Diffusion and Walks in an Expanding Medium

A classical-like derivation of the Fokker-Planck equation for diffusion in an expanding medium is presented. Our starting point is a conveniently generalized Chapman-Kolmogorov equation. We obtain analytical expressions for the Green's functions, their moments, and first-passage properties in expanding hyperspherical geometries. The behavior of these quantities is largely determined by the quantity we name Brownian conformal time $\tau(t)$ defined by $\dot{\tau} = 1/a^2$, where $a(t)$ is the expansion scale factor of the medium. We explicitly consider the cases of power-law expansion and exponential expansion. For the power-law case we find interesting crossover effects in the mixing effectiveness of the diffusion process depending on the value of the power-law exponent. The specific case of an exponential *contracting* medium is also discussed.

Santos B. Yuste
Universidad de Extremadura
santos@unex.es

Enrique Abad
Dpt. Fisica Aplicada.
Universidad de Extremadura
eabad@unex.es

Carlos Escudero
Departamento de Matematicas
Universidad Autonoma de Madrid
cel@icmat.es

Felipe Le Vot
Dpto. Fisica
Universidad de Extremadura
felipe.levot@gmail.com

MS161

Levy Walks: from Lineland to Higher Dimensions

The Lévy walk model has two main features distinguishing it from all other random walks: a finite velocity of moving particles, and the length of displacements that is power-law distributed. The model proved to be very successful in describing a large variety of superdiffusive phenomena across disciplines [Zaburdaev et al., Rev. Mod. Phys. 2015]. We will discuss the main properties of the model with an emphasis on practical applications. We will see how the basic model can be modified and extended to better match the challenges posed by complex real-life systems. One of the recent advances in this field is the generalisation of Lévy walks to two and three dimensions, where most of observed real-life dispersals occur. In higher dimensions, the Lévy walk model demonstrates yet another difference to classical random walks in that the geometry of the underlying random walk model is imprinted into the particle density profile at arbitrary long times.

Vasily Zaburdaev
Max-Planck-Institute for the Physics of Complex Systems
vzaburd@pks.mpg.de

MS162

A Stratified Three Dimensional Model for Ocean Flows That Includes Internal Waves

There is increasing reliance on autonomous vehicles for ocean observations. These vehicles are particularly sensitive to submesoscale currents and processes. Of special concern are buoyancy effects, vertical motions arising from internal waves and horizontal currents with significant vertical shear. It is important then to have reliable models of these processes so as to study the responses of these vehicles in realistic oceanic conditions. General circulation models can capture many of these processes, but they are computationally expensive and many do not include a prognostic vertical velocity. Here we report on some recent simulations with a simple three-dimensional model that includes both stratification and rotation. The analysis includes assessments of transport pathways and in particular how they depend on the interaction of submesoscale and mesoscale.

Henry Chang, Helga S. Huntley, Denny Kirwan
University of Delaware
changh@udel.edu, helgah@udel.edu, adk@udel.edu

MS162

Quantifying Material Transport in Geophysical Flows

We consider laboratory and numerical experiments on time-dependent multi-gyre flows that provide improved understanding of Lagrangian transport. This work presents current efforts in understanding the impact of geophysical fluid dynamics on underwater vehicle control and autonomy. The focus of the talk is on the use of collaborative vehicles to perform a variety of sensing tasks.

Eric Forgoston
Montclair State University
Department of Mathematical Sciences
eric.forgoston@montclair.edu

Ani Hsieh
Drexel University
mhsieh1@drexel.edu

Philip Yecko
Cooper Union
yecko@cooper.edu

MS162

Stochastic Parametrization in Wave Breaking and Weathering Processes

A stochastic parametrization for breaking dynamics of water waves is proposed. The parametrization derives from the analysis of Lagrangian particle paths, from computed and laboratory data. The Langevin dynamics combines a drift term largely informed by deterministic dynamics and a diffusion process that is based upon Matern processes. The data is further analyzed using ellipse ridge analyses, yielding a compact representation of this complex dynamics as well as the clean calculation of the residual flow from progressive multichromatic waves. A long term aim of this work is to derive sharp estimates of the dissipation due to breaking on waves and currents, a fundamental agent of momentum transfer between oscillatory and mean flows. Preliminary results of the projection of dissipation in the Lagrangian frame to the Eulerian frame makes this estimate practical in applied oceanography.

Juan M. Restrepo
Oregon State University
Department of Mathematics
restrepo@math.oregonstate.edu

Jorge Ramirez
Universidad Nacional de Colombia
jmramirezo@unal.edu.co

MS162

Geophysical Transport Structure, Reduced Order Modeling, and Connections with Field Experiments

Lagrangian techniques for revealing the most influential transport structures in geophysical flows are poised to make a significant impact on the prediction of material transport, with application to the assessment of hazards which spread in the ocean and atmosphere. However, more work is necessary to bridge the gap between powerful theoretical concepts and practical field experiments. Here we discuss some results relevant for real-time analysis and prediction of geophysical transport structures which have arisen from field applications. We discuss the incorporation of Lagrangian structure into reduced order modeling of geophysical flows and discuss challenges involved in forecasting atmospheric Lagrangian coherent structures, including the effect of spatial averaging and ensemble averaging. We also consider the local approximation of the most influential material surfaces via tracer release or monitoring of meteorological gradients.

Shane D. Ross
Virginia Tech
Engineering Mechanics program
sdross@vt.edu

MS163

Oscillations in a Parkinsonian Network

Muscle rigidity associated with Parkinsons disease (PD) is thought to be correlated with the loss of dopamine and the emergence of beta oscillations in the basal ganglia. As dopamine-producing neurons die off, synaptic connection strengths change leading to favoring of specific pathways. We first modeling average firing rates of a healthy basal ganglia using a systems-based approach. A PD basal ganglia is then modeled using the system's stability. Together these models can show disease progression and which connections are the most influential for this change - a question that is still under debate in the scientific community. These findings are then applied to particular therapeutic situations, hoping to find an understanding for how they work.

Michael Caiola
Emory University
mcaiola@emory.edu

MS163

Dynamics Underlying the Orientation Selectivity in Mouse V1

Experiments in mouse V1 have shown that excitatory neurons exhibit sharpening orientation selectivity(OS) while inhibitory neurons show broadening OS as the input contrast increases. To elucidate the mechanisms underlying these phenomena, we implemented essential findings from different experiments in the setup of our large-scale neuronal network simulation. And we successfully reproduced the contrast-dependent phenomena and unveiled its mechanism respectively in simulation and its analysis. Other important populational properties are also consist with experimental findings.

Wei Dai
Shanghai Jiao Tong University
Institute of Natural Science
guess@sjtu.edu.cn

MS163

Individual and Population Models of Insect Olfaction

When a locust detects an odor, the stimulus triggers a series of synchronous oscillations of the neurons in the antennal lobe, followed by slow dynamical modulation of the firing rates. I model this behavior using an Integrate-and-Fire neuronal network with excitatory and inhibitory neurons, each with a fast and slow inhibitory conductance response. I derived a coarse-grained model for each (excitatory and inhibitory) neuronal population, which allows for more detailed analysis of the olfaction mechanisms.

Pamela B. Pyzza
Ohio Wesleyan University
Dept. of Mathematics and CS
pbpyzza@owu.edu

Gregor Kovacic
Rensselaer Polytechnic Inst
Dept of Mathematical Sciences
kovacg@rpi.edu

David Cai
Courant Institute for Mathematical Sciences, NYU
Shanghai Jiao-Tong University
cai@cims.nyu.edu

MS163

High Dimensional Two-sample Test on Neuronal Data

Statistical methods typically require independent samples. To apply recently-developed statistical methods to perform high dimensional two-sample test in neuroscience, we propose an efficient method to pretreat neuronal data, so samples become independent. This is achieved by transferring correlations between samples into those between dimensions. Our results show that the discriminability of high dimensional statistical method under our pretreatment is much better than methods that use only a small number of neurons in a short recording.

zhiqin J. Xu
Department of Mathematics and Institute of Natural Sciences
Shanghai Jiao Tong University
zhiqinxu@nyu.edu

MS164

Alternans in Action Potential Amplitude and Not in Duration As a Mechanism for Conduction Block

and the Initiation of Fibrillation

It is widely believed that one of the major life-threatening transition to chaotic fibrillation occurs via spiral-wave breakup that is preceded by spatiotemporal dispersion of refractoriness due to alternations in the duration of the cardiac action potential (AP). However, recent clinical and experimental evidence suggests that other characteristics of the AP may contribute to, and perhaps drive, this dangerous dynamical instability. To identify the relative roles of AP characteristics, we performed experiments in rabbit hearts under conditions to minimize AP duration dynamics which unmasked pronounced AP amplitude alternans just before the onset of fibrillation. We used a simplified ionic cell model to derive a return map and a stability condition that elucidates a novel underlying mechanism for AP alternans and spiral breakup. We found that inactivation of the sodium current is key to develop amplitude alternans and which is directly connected to conduction block and initiation of arrhythmias. Simulations in 2D in which AP amplitude alternation led to turbulence confirm our hypothesis. Our results suggest novel approaches for preventing the dangerous transition to fibrillation.

Diandian Diana Chen
Georgia Institute of Technology
School of Physics
dchen87@gatech.edu

Flavio H. Fenton
Georgia Institute of Technology
flavio.fenton@physics.gatech.edu

MS164

Modeling Framework to Delineate Optimized Drug Action for Atrial Spiral Wave Termination

Atrial fibrillation (AF) is the most common type of sustained reentrant cardiac arrhythmia. Antiarrhythmic drugs for the modulation of the cell nonlinear voltage dynamics have long been used to terminate AF reentrant activity. However, limited drug efficacy and the risk of important complications lead to decrease usage. Thus, there is a strong interest in the development of AF-selective antiarrhythmic drugs. Mathematical modeling of cardiac nonlinear models and drug action is central to this optimization. Careful identification of pharmacodynamic parameters optimized for selective actions on atrial tissue during AF is central to the method. Such an approach also opens the way to multiple-channel blockade therapy (sodium and potassium channel block for example). The ultrarapid potassium current (I_{Kur}) is an interesting target for atrial-specific block as it is found in atria but not in ventricles, thus decreasing the ventricular arrhythmia risk. To date, an important step in the method is to evaluate the steady-state changes induced to the action potential and conduction velocity. Here, we show that this approach can be limited as only small changes in APD are found for I_{Kur} block while important transient variations in APD are linked in simulated 2D reentry termination. Roughly modeling the pharmacodynamic of the agent by addition of the time-constant in effective block highlight its importance on the termination of reentrant activity.

Philippe Comtois
Institute of Biomedical Engineering,
Universite de Montreal
philippe.comtois@umontreal.ca

MS164

Adaptive Control of Chaotic Dynamics in Excitable Media

During cardiac arrhythmias like ventricular fibrillation the spatial-temporal dynamics of the heart determined by spiral or scroll waves is highly chaotic. Observations in experiments and simulations show, that the chaotic behavior is not necessarily persistent, but may also be transient. Here we investigate in numerical simulations how the average lifetime of such a chaotic transient can be reduced passively by changing the system properties of 2D and 3D systems and discuss the possibilities of how to actively reduce the transient time significantly (termination) by recent control strategies.

Thomas Lilienkamp
Max Planck Institute for Dynamics and Self-Organization
Biomedical Physics Research Group
Thomas.Lilienkamp@ds.mpg.de

Stefan Luther, Ulrich Parlitz
Max Planck Institute for Dynamics and Self-Organization
Research Group Biomedical Physics
stefan.luther@ds.mpg.de, ulrich.parlitz@ds.mpg.de

MS164

Closed-Loop Feedback Control of Cardiac Alternans in the Heart

Previous studies have established a link between alternans, a beat-to-beat alternation in cardiac action potential duration (APD), and ventricular arrhythmias, suggesting that elimination of alternans could lead to the prevention of arrhythmias in the heart. Over the past years, several attempts have been made to control alternans. Some attempts involved the control of APD or diastolic interval (DI) in isolated cells based on the feedback from a microelectrode recordings. In addition, the majority of control approaches target basic cycle length (BCL) while assuming periodic pacing: APD+DI=BCL. Recently, we demonstrated, using single cell numerical simulations, that eliminating the dependence of the DI on the preceding APD, i.e. maintaining a constant DI pacing, prevents the formation of alternans. However, implementation of constant DI pacing requires the development of a sophisticated control system that can sense, track and measure APD and DI in real-time. Here, we extended and validate the antiarrhythmic benefits of constant DI pacing in 1D cables of canine and human cardiac cells. In addition, we developed a 2D closed-loop feedback control system that enabled the detection of APDs and providing real time constant DI pacing from various single pixels based on optical mapping recordings from ex-vivo rabbit heart in real-time. Our method incorporates beat-by-beat DI control and provides the spatiotemporal flexibility to target alternans in the whole heart.

Alena Talkachova, Kanchan Kulcarni
University of Minnesota
talkacal@umn.edu, kulka101@umn.edu

Sharon Zlochiver
Tel-Aviv University

sharon.zlochiver@gmail.com

MS165

Structural and Practical Identifiability of Stochastic, Mechanistic Cancer Models

Multistage clonal expansion (MSCE) models, a class of mechanistic, continuous-time Markov models, are commonly used to connect population-level cancer incidence to the putative underlying biology of carcinogenesis by parameter estimation. Identifiability, then, tells us what aspects of the model we can make inferences about. Few tools are available to assess the identifiability of stochastic models, but, because age-specific cancer incidence data corresponds to the model hazard, we can leverage the Kolmogorov equations for the probability generating functions and use the differential algebra approach to assess the structural identifiability of this class of models, an approach that can be used for time-to-event stochastic models more generally. However, this approach assumes available data can identify features along the entire trajectory of the model hazard, and certain salient features appear only several orders of magnitude beyond the scale of a human lifespan. We use a profile-likelihood approach to show that this practical limitation restricts our inference to three, biologically-relevant parameter combinations, regardless of the structural identifiability of the MSCE model used. In particular, for each model we can identify only the product of the initiation rates, the net cell proliferation rate, and the scaled malignant conversion rate.

Andrew Brouwer
University of Michigan
brouweaf@umich.edu

MS165

Identifiability and Parameter Estimation in Modeling Biological Dynamics

Connecting dynamic models with data to yield predictive results often requires a variety of parameter estimation, identifiability, and uncertainty quantification techniques. These approaches can help to determine what is possible to estimate from a given model and data set, and help guide new data collection. In this talk, we will discuss approaches to both structural and practical identifiability analysis. Using a range of examples from Hodgkin-Huxley models, to cholera spread, to cancer, we illustrate some of the potential difficulties in estimating the relative contributions of different pathways, and show how alternative data collection may help resolve unidentifiability. We also illustrate how even in the presence of large uncertainties in the data and model parameters, it may still be possible to successfully forecast the system dynamics.

Marisa Eisenberg
University of Michigan
marisae@umich.edu

MS165

Goodness of Fit in Differential Equation Models: Misspecified Rates Or Misspecified States?

This talk considers the statistical evidence for evolution in laboratory-based ecological experiments. We examine data from a chemostat experiment in which algae are grown on nitrogen-rich medium and rotifers are introduced as a predator. The resulting data exhibit dynamics that do not correspond to those generated by classical ecological models. A hypothesized explanation is that more than one algal species is present in the chemostat. We assess the statistical evidence for this claim in terms of three potential causes of lack of fit for standard differential equation models for this system: (i) unmodeled stochastic forcing, (ii) mis-specified functional forms and (iii) mis-specified state variables. Here the proposed explanation of multiple algal species corresponds to hypothesis (iii). Tests between these hypotheses are achieved by representing lack of fit in terms of time-varying parameters and assessing the relationship between these time varying parameters and existing state variables with statistical significance assessed through bootstrap and permutation methods. While our tests suggest that observed dynamics are well-matched by multiple-species models, alternative causes for lack of fit cannot be ruled out. We conclude with an examination of the use of control theory to design inputs into chemostat systems to improve parameter estimation and power to detect missing components.

Giles Hooker
Biostatistics and Computational Biology Department
Cornell University
giles.hooker@cornell.edu

MS165

Identifiability of Linear Compartmental Models

Parameter identifiability analysis addresses the question of which unknown parameters of a model can be determined from given input-output data. In this talk, we discuss structural identifiability analysis, which addresses whether or not the model parameters can be determined from perfect input-output data (noise-free and of any duration required) and is an important step in the parameter estimation problem. Many linear ODE models used in systems biology are unidentifiable, which means that parameters can take on an infinite number of values and yet yield the same input-output data. We study a particular class of unidentifiable models and find conditions to obtain identifiable reparametrizations of these models. In particular, we use a graph-theoretic approach to analyze the models and show that graphs with certain properties allow a monomial scaling reparametrization over identifiable functions of the parameters. We also examine conditions to obtain identifiability for this class of models, and in particular, show how identifiability can be determined by simply looking at the graphical structure of these linear compartmental models.

Nicolette Meshkat
North Carolina State University
nmeshkat@scu.edu

MS166

Central Configurations of the N-Body Problem with Generalized Potentials

The behavior of some central configurations in the N-body problem are investigated when the central potential exponent is changed.

Marshall Hampton
University of Minnesota, Duluth

mhampton@d.umn.edu

MS166

Existence, Stability, and Symmetry of Relative Equilibria with a Dominant Vortex

We will consider relative equilibria in the n-vortex problem with one dominant vortex and N much smaller vortices. The dimension of the problem can be reduced by taking an infinitesimal circulation limit, resulting in the $(1+N)$-vortex problem. In this talk we generalize a previously known reduction to allow for circulations of varying signs and weights, and then focus on the case where $N = 3$. Here we find conditions for symmetry in the relative equilibria configurations, and consider the stability of the continuations from the infinitesimal circulation case back to nonzero, small circulation. Moreover, we show that there are stable asymmetric relative equilibria. Techniques from algebraic geometry are used to count families of relative equilibria at different circulation values.

Alanna Hoyer-Leitzel
Mathematics Department
Bowdoin College
ahoyerle@mtholyoke.edu

MS166

Morse Theory and Stability of Relative Equilibria in the Planar N-Vortex Problem

The planar n-vortex problem is a Hamiltonian system of differential equations that effectively approximates vorticity evolution in fluid dynamics. Since collisions between point vortices must be excluded, the topology of the underlying configuration space is nontrivial and Morse theory can be applied to yield interesting results. We identify an explicit connection between the Morse index of a critical point of the Hamiltonian restricted to a level surface of the angular impulse and the eigenvalues of the corresponding relative equilibrium solution (a rigidly rotating configuration). The Morse inequalities are then used to classify the stability (or instability) of all relative equilibria for some particular cases in the four-vortex problem. An overview of topological results and open questions related to this work will also be provided.

Gareth E. Roberts
Dept. of Mathematics and C.S.
College of the Holy Cross
groberts@holycross.edu

MS166

Remarks on the Central Configurations of Four Bodies

The study of the central configurations in the n-body problem is one important area of Celestial Mechanics. The finiteness of central configuration was listed by Stephen Smale as problem 6 on his list of problems for this century. In the four-body case the finiteness was proved by Marshall Hampton and Rick Moeckel in 2006. There are, however, many things we still need to understand in the case of four bodies. One well known conjecture by Alain Albouy states that there is only one convex central configuration for each cyclic ordering of the masses. In this talk we will revisit some results for the four-body problem by extending them and presenting new proofs.

Manuele Santoprete
Wilfrid Laurier Univerisity
msantoprete@wlu.ca

MS167

Absolute Instabilities of Travelling Waves Solutions in a Keller-Segel Model

In this talk we investigate the spectral stability of travelling wave solutions in a Keller-Segel model of bacterial chemotaxis with a logarithmic chemosensitivity function and a constant, sublinear, and linear consumption rate. We locate the essential and absolute spectrum of the associated linear operators and find that all travelling wave solutions have essential spectrum in the right half plane. However, we show that in the case of constant or sublinear consumption there exists a range of parameters such that the absolute spectrum is contained in the open left half plane and the essential spectrum can thus be weighted into the open left half plane. For the constant and sublinear consumption rate models we also determine critical parameter values for which the absolute spectrum crosses into the right half plane, indicating the onset of an absolute instability of the travelling wave solution. We observe that this crossing always occurs off of the real axis. This work is done in conjunction with Peter van Heijster and Robert Marangell.

Paige Davis
Queensland University of Technology
pn.davis@hdr.qut.edu.au

MS167

Determining the Critical Spectrum About the Origin Using Lin's Method

Pattern solutions often arise as perturbations from a simpler limit structure. One can think of a family of periodics that accompany a homoclinic pulse, multi-pulse solutions bifurcating from a primary pulse or patterns arising from a concatenation of slow and fast orbit segments in singularly perturbed problems. Nonlinear stability of these patterns is in many cases decided by the spectral properties of the linearization about the pattern. Exploiting the limit structure often leads to asymptotic control over the spectrum. However, asymptotic spectral control is insufficient to decide upon stability if there is non-trivial spectrum shrinking to the origin in the asymptotic limit. In such cases a higher order analysis is necessary to determine the spectral geometry about the origin. This can be achieved using Lin's method.

Björn De Rijk
University of Stuttgart
Institut für Analysis, Dynamik und Modellierung
bjoern.derijk@mathematik.uni-stuttgart.de

MS167

Stability of Fronts in a Diffusive Model for Porous Media Combustion

We consider a model of combustion in hydraulically resistant porous media. There are several reductions of this systems that can be used to understand the evolution of the combustion fronts. In this presentation, we discuss this model with the Lewis number chosen in a specific way. First, we, in addition, consider initial conditions of a specific form. We then show that the stability results for that system extend to the fronts in the full system with the same

Lewis number. The fronts are either absolutely unstable or convectively unstable.

Anna Ghazaryan
Department of Mathematics
Miami University
ghazarar@muohio.edu

Stephane Lafortune
College of Charleston
Department of Mathematics
lafortunes@cofc.edu

Peter McLarnan
Miami University
peterm@cs.earlham.edu

MS167

Coherent Structures in Run-and-Tumble Processes

Motivated by the observation of rippling patterns in colonies of Myxobacteria, we study a "simplest' modes for dynamics of populations, where agents run either left or right with constant speed, and reverse direction depending on local population densities in a nonlinear fashion. Linear analysis and simulations reveal how shot noise perturbations can give rise to rippling behavior and predict wavelengths. The talk will explain the basic mechanism and highlight the relevance of a systematic stability analysis for the coherent structures observed.

Arnd Scheel
University of Minnesota
School of Mathematics
scheel@math.umn.edu

MS168

Synchronization in Networks with Multiple Interaction Layers

The structure of many realworld systems is best captured by networks consisting of several interaction layers. Understanding how a multilayered structure of connections affects the synchronization properties of dynamical systems evolving on top of it is a highly relevant endeavour in mathematics and physics, and has potential applications to several societally relevant topics, such as power grids engineering and neural dynamics. We propose a general framework to assess stability of the synchronized state in networks with multiple interaction layers, deriving a necessary condition that generalizes the Master Stability Function approach. We validate our method applying it to a network of Rssler oscillators with a double layer of interactions, and show that highly rich phenomenology emerges. This includes cases where the stability of synchronization can be induced even if both layers would have individually induced unstable synchrony, an effect genuinely due to the true multilayer structure of the interactions amongst the units in the network.

Jesus Gomez-Gardenes
Universidad de Zaragoza
gardenes@gmail.com

Charo I. del Genio
School of Life Sciences
University of Warwick, U.K.
C.I.del-Genio@warwick.ac.uk

Stefano Boccaletti
CNR-Istituto dei Sistemi Complessi
stefano.boccaletti@isc.cnr.it

Ivan Bonamssa
Bar Ilan University, Israel
ivan.bms.2011@gmail.com

MS168

Chimera States in Continuous Media

The defining property of chimera states is the coexistence of coherent and incoherent domains in symmetric coupled systems. The recent realization that such states might be common in oscillator networks raises the question of whether an analogous phenomenon can occur in continuous media. In this presentation, I will show that chimera states can exist in continuous systems even when the coupling is strictly local, as in many fluid and pattern forming media. Using the complex Ginzburg-Landau equation as a model system, we characterize chimera states consisting of a coherent domain of a frozen spiral structure and an incoherent domain of amplitude turbulence. We show that in this case, in contrast with discrete network systems, fluctuations in the local coupling field play a crucial role in limiting the coherent regions. We suggest these findings shed light on new possible forms of coexisting of order and disorder in fluid systems.

Zachary G. Nicolaou
Northwestern University
zachary.nicolaou@northwestern.edu

Hermann Riecke
Applied Mathematics
Northwestern University
h-riecke@northwestern.edu

Adilson E. Motter
Northwestern University
motter@northwestern.edu

MS168

Using Symmetries and Equitable Partitions Together to Find All Synchronization Clusters and Their Stability

Many networks of coupled oscillators are observed to produce patterns of synchronized clusters where all the oscillators in each cluster have exactly the same dynamical trajectories in state space, but not the same as oscillators in other clusters. It has been difficult to predict these clusters in general. We show the intimate connection between network symmetry and cluster synchronization. We apply computational group theory to reveal the clusters and determine their stability. Other synchronization clusters are possible in addition to the symmetry clusters (SC). These are equitable partitions (EP) of the network. We show that the EP can be constructed by the merging of appropriate SC. We show that this construction also allows the derivation of further simplified stability (variational) equations for the EP case thus allowing the SC and EP approaches to compliment each other. The connection between symmetry and cluster synchronization is experimentally explored using an electro-optic network.

Louis M. Pecora
U.S. Naval Research Laboratory
louis.pecora@nrl.navy.mil

Francesco Sorrentino
University of New Mexico
Department of Mechanical Engineering
fsorrent@unm.edu

Aaron M. Hagerstrom
University of Maryland
aaron.hagerstrom@gmail.com

Rajarshi Roy
University of Maryland, College Park, MD, USA
lasynch@gmail.com

Thomas E. Murphy
University of Maryland, College Park
Dept. of Electrical and Computer Engineering
tem@umd.edu

MS168

Controlling Synchronous Patterns in Complex Network of Coupled Chaotic Oscillators

Although the set of permutation symmetries of a complex network could be very large, few of them give rise to stable synchronous patterns. Here we present a general framework and develop techniques for controlling synchronization patterns in complex network of coupled chaotic oscillators. Specifically, according to the network permutation symmetry, we design a small-size and weighted network, namely the control network, and use it to control the large-size complex network by means of pinning coupling. We argue mathematically that for any of the network symmetries, there always exists a critical pinning strength beyond which the unstable synchronous pattern associated to this symmetry can be stabilized. The feasibility of the control method is verified by numerical simulations of both artificial and real-world networks and demonstrated experimentally in systems of coupled chaotic circuits. Our studies show the controllability of synchronous patterns in complex networks of coupled chaotic oscillators.

Xingang Wang
Zhejiang University, China
wangxg@snnu.edu.cn

MS169

A Data-Driven Distributed Algorithm for Nonlinear Mode Estimation in Power Systems

We present a distributed optimization algorithm for estimating nonlinear oscillation modes of power systems using real-time Synchrophasor data. In our previous works we have shown that linear mode estimation can be cast as a linear least squares estimation problem for the coefficients of the characteristic polynomial of the power system model, assuming the order of the polynomial to be known. For nonlinear mode estimation, however, such a polynomial with a fixed order does not exist any more. Instead an appropriate length of data needs to be selected based on which the effective order of the estimation is decided. If the estimation has to be carried out in a distributed fashion between multiple phasor data concentrators, then operators would prefer this data length to be as small as possible without sacrificing accuracy of the estimation. To address this problem, in this talk we will present an algorithm by which the length of the measured variables can be reduced by appropriate use of singular value decomposition and forgetting factors associated with the data Hankel matrices. Thereafter, we will use this reduced data set for running a distributed estimation algorithm based on alternating direction multiplier method (ADMM). We will illustrate the convergence, synchronization, and real-time constraints associated with this entire process with examples drawn from IEEE power system models.

Aranya Chakrabortty
North Carolina State University
achakra2@ncsu.edu

Yoshihiko Susuki
Kyoto University, JST
susuki@eis.osakafu-u.ac.jp

MS169

Finding Slow Modes and Accessing Very Long Timescales in Molecular Dynamics

The sampling problem, i.e. the difficulty to sample rare events along the slow modes, is a key problem in molecular dynamics and many other microscopic dynamical systems. In thermal equilibrium, where the dynamics have a stationary state and are statistically reversible, we can derive a variational approach to approximate the eigenfunctions of the Koopman operator / transfer operator. Algorithmically, this can be achieved by computing covariance matrices from a set of basis functions and obtaining the optimal approximation of eigenfunctions from the eigenvectors of a generalized eigenvalue problem. This approach turns out to be identical to the more recently introduced Extended dynamic mode decomposition, and it has similarities the dynamic mode decomposition. We will show how the eigenfunction approximates can be used in order to approximate the essential dynamics in complex many-body systems and how this information can be exploited to enhance the sampling of rare events.

- F. Nueske et al: Variational Approach to Molecular Kinetics. J. Chem. Theory Comput., 10, 1739-1752 (2014)
- F. Noe and F. Nueske: A variational approach to modeling slow processes in stochastic dynamical systems. SIAM Multiscale Model. Simul., 11, 635-655 (2013)

Frank Noe
FU Berlin
frank.noe@fu-berlin.de

MS169

Assessment of Voltage Collapse Phenomena in Power Grids Based on Continuous Spectrum of the Koopman Operator

Large decrease or destabilization of voltage amplitudes often disturbes normal operation of modern power grids. The so-called voltage collapse and associated dynamic phenomena have been widely studied in power grids engineering and nonlinear dynamical systems. In this talk, we revisit the dynamics of voltage collapse phenomena in terms of spectral properties of the Koopman operator. We show that one dynamic signature of decrease of voltage amplitudes is characterized by continuous spectrum of the Koopman operator for a underling mathematical model. This provides a novel method for detecting the occurrence of voltage collapse directly from data without development of mathematical models. Effectiveness of the method is discussed with its application to data obtained by not only detailed power-grid simulations but also practical measurement.

Yoshihiko Susuki
Kyoto University, JST
susuki@eis.osakafu-u.ac.jp

Kyoichi Sako, Fredrik Raak
Kyoto University
k-sako@dove.kuee.kyoto-u.ac.jp,
f-raak@dove.kuee.kyoto-u.ac.jp

Takashi Hikihara
Department of Electrical Engineering
Kyoto University
hikihara.takashi.2n@kyoto-u.ac.jp

MS169

Koopman Operator Theory, Memory Effects, and Fractional Order Dynamical Systems

Koopman operator theory has recently become a practical tool for data-driven analysis of dynamical systems. The theory rests on an inherent assumption that the observables follow a Markov rule of memoryless evolution. However, memory effects may naturally arise in the dynamics of observables as the complexity of the system increases. For example, the dynamics of a system interacting with an environment is generally non-Markovian, and in special cases open systems may exhibit long-term memory effects characterized by fractional order derivatives in time. We discuss first steps toward a generalized Koopman operator theory that is compatible with memory effects and fractional calculus. We focus on a simple nonlinear system that is useful for testing the theoretical ideas. Since Koopman operator theory is notably amenable to numerical treatment, we also outline plans for developing generalized numerical methods that in principle could be used to detect memory effects in data and subsequently construct an appropriate model.

Adam Svenkeson, Bryan Glaz
Army Research Laboratory
adam.j.svenkeson.civ@mail.mil, bryan.j.glaz.civ@mail.mil

MS170

Phase-Locking in a Neuronal Networks with Synaptic Depression

We derive a 2-dimensional map to investigate the origins of bistability of phase-locked periodic solutions in a pair of inhibitory neurons coupled via depressing synapses. We show that stable solutions that exist in the absence of synaptic depression can undergo saddle-node bifurcations leading to distinct high- and low-frequency out-of-phase solutions becoming concurrently stable. The method of analysis applies to any Type I neuron and involves using phase resetting curves and geometric analysis.

Zeynep Akcay
Queensborough Community College
zakcay@qcc.cuny.edu

Xinxian Huang
Department of Mathematical Sciences
New Jersey Institute of Technology
xh28@njit.edu

Farzan Nadim
New Jersey Institute of Technology
& Rutgers University
farzan@njit.edu

Amitabha Bose
New Jersey Institute of Technology
bose@njit.edu

MS170

A Singulartity Theory Approach to Homeostasis

Homeostasis occurs when some output variable remains approximately constant as input parameters λ vary over some intervals. First, we discuss the effect of coordinate changes on the input-output map associated to homeostasis. Second, we formulate homeostasis in the context of singularity theory by replacing 'approximately constant over an interval' with 'zero derivative of the output with respect to the inputs at a point'. Unfolding theory then classifies all small perturbations of the input-output function. In particular, in one input systems the 'chair' singularity, which has been shown by Best, Nijhout, & Reed to be especially important in applications, is discussed in detail. Its normal form and universal unfolding $\lambda^3 + a\lambda$ is derived and the region of approximate homeostasis is deduced. This normal form shows how a one output system can deform from non-homeostasis to homeostasis. In two input systems the hyperbolic umbilic can also organize evolution to homeostasis.

Martin Golubitsky
Ohio State University
Mathematical Biosciences Institute
golubitsky.4@osu.edu

Ian Stewart
University of Warwick
Mathematics Institute
ins@maths.warwick.ac.uk

MS170

Chaos, Spike-Adding, and Mixed-Mode Oscillations in a Nonlinear Neuronal Model with Resets

Neuronal models with resets, or hybrid models, can capture complicated dynamics in a relatively low-dimensional setting. I will discuss two activity patterns, chaos and mixed-mode oscillations (MMOs), in a general class of these hybrid models. I will explain the mechanisms underlying chaos and MMOs as well as the pathways through which various model parameters can modulate the resulting model dynamics. The analysis makes use of a one-dimensional adaptation map. I will discuss how under parameter variations, chaos emerges in association with period-incrementing transitions, and how, in another regime, rotation theory for circle maps can be used to elucidate the MMO dynamics.

Jonathan E. Rubin
University of Pittsburgh
Department of Mathematics
jonrubin@pitt.edu

Justyna Signerska-Rynkowska
Faculty of Applied Physics and Mathematics
Gdansk University of Technology
jsignerska@mif.pg.gda.pl

Jonathan D. Touboul
The Mathematical Neuroscience Laboratory
College de France & INRIA Paris
jonathan.touboul@college-de-france.fr

Alexandre Vidal
University of Evry
Laboratoire de Mathématiques et Modélisation d'Evry (LaMME)
alexandre.vidal@univ-evry.fr

MS170

Temperature Sensitivity of PO/AH Neurons

Thermoregulatory responses are partially controlled by the preoptic area and anterior hypothalamus (PO/AH), which contains a mixed population of temperature-sensitive and insensitive neurons. In [Wechselberger et al, 2006] based on physiological data, a Hodgkin-Huxley-like conductance based model was constructed. This model suggests that most PO/AH neurons have the same types of ionic channels, but different levels of channel expression can explain the inherent properties of the various types of temperature-sensitive and insensitive neurons which is encoded in their frequency sensitivity relative to temperature. Here we present a detailed bifurcation analysis of this model to confirm these observations. We focus on three main physiological bifurcation parameters, the temperature T and the maximum conductances of two specific background potassium leak channels, g_{task} and g_{trek}, that are known to be expressed in these PO/AH neurons. These three bifurcation parameters are sufficient to explain the dynamics of PO/AH neurons observed in experiments.

Martin Wechselberger, Timothy Roberts
University of Sydney
wm@maths.usyd.edu.au, trob5740@uni.sydney.edu.au

MS171

Metastable States for an Aggregation Model with Noise

We consider the aggregation equation with kernels that generate patterns consisting of two delta-concentrations. Without noise, there is a one-parameter family of admissible equilibria that consist of two concentrations whose mass is not necessary equal. When a small amount of noise is added, the heavier concentration leaks its mass towards the lighter concentration over a very long time scale, eventually resulting in the equilibration of the two masses. We use exponentially small asymptotics to derive the long-time ODEs that quantify this mass exchange. Our formal computations show that adding noise destroys the degeneracy in the equilibrium solution and leads to a unique symmetric steady state.

Joep Evers, Theodore Kolokolnikov
Dalhousie University
j.evers@dal.ca, tkolokol@mathstat.dal.ca

MS171

Effects of Cell Geometry on Reversible Vesicular Transport

A major question in biology concerns the mechanics behind the motor- driven transport and delivery of vesicles to localized regions of a given cell. In the case of neurons, experimental evidence suggests that the distribution of vesicles along the axon is relatively uniform and that vesicular delivery to synapses is reversible. Recent models of vesicular delivery to synapses have made explicit the crucial role that reversibility in vesicular delivery to synapses plays in achieving uniformity in vesicle distribution, so called synaptic democracy. We will illustrate this principle by first discussing a one-dimensional model of motor transport and vesicle delivery on a semi-infinite domain and show how reversibility in vesicle delivery facilitates synaptic democracy. We will then discuss more general models that account for exclusion effects between motors traveling in bulk and higher dimensional models on the disk, sphere, and Cayley tree that illustrate how uniformity in vesicle density may be achieved in cells in general. In all cases we find that uniformity in vesicle delivery to target sites is facilitated by allowing for reversibility in vesicle delivery, provided that the velocity of cargo-carrying motors is not significantly slowed by the load of the cargo.

Bhargav R. Karamched
University of Utah
Salt Lake City, UT
karamche@math.utah.edu

MS171

First-Passage Time to Clear the Way for Receptor-Ligand Binding in a Crowded Environment

I will present theoretical support for a hypothesis about cell-cell contact, which plays a critical role in immune function. A fundamental question for all cell-cell interfaces is how receptors and ligands come into contact, despite being separated by large molecules, the extracellular fluid, and other structures in the glycocalyx. The cell membrane is a crowded domain filled with large glycoproteins that impair interactions between smaller pairs of molecules, such as the T cell receptor and its ligand, which is a key step in immunological information processing and decision-making. A first passage time problem allows us to gauge whether a reaction zone can be cleared of large molecules through passive diffusion on biologically relevant timescales. I combine numerical and asymptotic approaches to obtain a complete picture of the first passage time, which shows that passive diffusion alone would take far too long to account for experimentally observed cell-cell contact formation times. The result suggests that cell-cell contact formation may involve previously unknown active mechanical processes.

Jay Newby
University of North Carolina-Chapel Hill
jaynewby@email.unc.edu

MS171

Kinetic Monte Carlo Methods for Computing First Capture Time Distributions in Models of Diffusive Absorption

Consider the pistil of a flower waiting to catch a grain of pollen, a lymphocyte waiting to be stimulated by an antigen to produce antibodies, or an anteater randomly foraging for an ant nest to plunder. Each of these problems can be modeled as a diffusive process with a mix of reflecting and absorbing boundary conditions. One can characterize the agent (pollen, antigen, anteater) finding its target (pistil, lymphocyte, ant nest) as a *first passage time* (FPT) problem for the distribution of the time when a particle executing a random walk is absorbed. In this talk we will examine a hierarchy of FPT problems modeling planar or spherical surfaces with a distribution of circular absorbing traps. We will describe a Kinetic Monte Carlo (method that exploits exact solutions to accelerate a particle-based simulation of the capture time. A notable advantage of these methods is that run time is independent of how far from the traps one begins. We compare our results with asymptotic approximations of the FPT distribution for particles that start far from the traps. Our goal is to validate the efficacy of homogenizing the surface boundary conditions, replacing the reflecting (Neumann) and absorbing (Dirichlet) boundary conditions with a mixed (Robin) boundary condition.

Daniel Schmidt
Harvey Mudd College
danielschmidt24@gmail.com

Andrew J. Bernoff
Harvey Mudd College
Department of Mathematics
ajb@hmc.edu

Alan E. Lindsay
Applied Computational Mathematics and Statistics
University of Notre Dame
a.lindsay@nd.edu

MS172

Using Recurrences to Detect Non Stationary Behavior of Time Series

We explore the utility of a nonlinear recurrence measure, the Determinism, to identify and quantify transitions between segments with distinct statistical properties in the output signals of nonlinear dynamical systems, and to infer coupling between systems. We demonstrate that this measure is sensitive to detect even small variations in the dynamics of a system by studying stationarity breaking in the signal output displayed by another system coupled to the first. To test our approach we apply the technique to the dynamics of two physiological systems, activation in the hippocampus brain area and in the locomotor system in mice during sleep. We analyze the respective output signals of these two systems – evasively obtained hippocampal local field potential and noninvasive locomotor accelerometer sensor signal. We demonstrate that small-amplitude short bursts in the accelerometer signal (representing micro-arousals during sleep) are associated with abrupt transitions in the profile of the recurrence quantifier. Moreover we find that stationarity breaking, associated with abrupt transition in the determinism, consistently precedes each arousal burst in the Determinism signals by few seconds.

Sergio R. Lopes
Paraná Federal University, Brazil
sergio.roberto.lopes@gmail.com

MS172

Recurrency Density Enchanced Approach for Time Series Analysis

We present a transformation method, entitled Recurrence Density Enhancement Approach (RDE), that aims to highlight the main recurrence structures of a given recurrence plot (RP). Our method results in a figure with a reduced number of points yet preserving the main and fundamental properties of the original plot. The existing measures of quantification analysis are applied to characterize the underlying dynamical system. Our evaluation results indicate that our proposed appproach allows to discriminate different dynamic regimes adequately, while using a reduced set of points from the original RP.

Elbert E. Macau
INPE - Brazilian National Institute for Space Research
LAC - Laboratory for Computing and Applied Mathematics
elbert.macau@inpe.br

MS172

Network Inference Meets Nonlinear Time Series: Challenges and Solutions

Recent years have seen a large increase in the availability of data. In fact, increasing amounts of data play a key role in every aspect of our lives, such as biology, e.g. genomic data, medicine, e.g. functional magnetic resonance imaging or electroencephalography, and data mining in the social sciences or digital economies. Dealing with these data sets efficiently determines the success of the projects, treatments, assessments, and analyses. The necessity to better understand data has led to an outburst of research into advanced methods of data analysis. The inference of networks underlying complex systems is of utmost importance. Especially when dealing with complex data sets the algorithms for network inference should meet certain requirements such as dealing with truly multivariate data, accounting for various concurrent noise sources, and addressing both linear and non-linear systems. A multitude of algorithms has been developed to address these extremely challenging requirements. This is partly because a rigorous mathematical framework, i.e., a theory of a suitable highly versatile class of mathematical models to comprise these features, is challenging. In this talk, the challenges as well as various methods will be introduced, discussed and compared. This results in a comprehensive overview of techniques that exists to tackle one of the key challenges of data based modelling: The detection of directed interactions from time series in nonlinear systems.

Bjoern Schelter
Institute for Complex Systems and Mathematical Biology
b.schelter@abdn.ac.uk

Marco Thiel
University of Aberdeen
Scotland
m.thiel@abdn.ac.uk

MS173

A Computational Model of Hemostasis

Hemostasis is the process by which a blood clot forms to prevent bleeding. The clot size, structure and time to formation all depend on the local hemodynamics and the nature of the injury. Our previous computational models were developed to study intravascular clot formation, a process confined to the interior of a single vessel. Here we present the first computational model of extravascular clot formation (hemostasis) in which blood through a single vessel initially escapes through a hole in the vessel wall and out a separate injury channel. The model consists of a system of partial differential equations that describe blood coagulation biochemistry, platelet aggregation, and hemodynamics, solved via the finite element method. In the model, formation of a blood clot occludes the injury channel and stops flow from escaping while blood in the main vessel retains its fluidity. We discuss the different biochemical and hemodynamic effects on clot formation using distinct geometries representing intra- and extravascular injuries.

Nicholas Danes
Applied Mathematics & Statistics
Colorado School of Mines
ndanes@mines.edu

Karin Leiderman
Colorado School of Mines
kleiderman@mines.edu

MS173

Drug Delivery to the Brain: Mathematical Challenges in Breaking the Blood-Brain Barrier

Incidence rates of neurodegenerative diseases and brain cancers continue to rise. Many brain diseases can be treated by drugs and research in biomedicine has resulted in powerful compounds to treat Parkinson's Disease, Alzheimer's Disease, and brain tumors. The problem facing pharmaceutical innovators is to deliver a drug specifically to a target site, in the required amount, at the required rate, and at the appropriate time. In other words, they must give answers to the primary questions: How much? When? How often? Where? Drug delivery to the brain is particularly challenging due to the blood-brain barrier: some molecules cannot permeate the barrier at all, and others require active transport to make it through. One solution is to package the drugs in nano-particles that release their cargo in response to an external trigger, such as temperature or acoustical pressure. In this talk I will present a mathematical model that describes the delivery of a drug to a specific region of the brain with the help of liposomes triggered by focused ultrasound. I will discuss the challenges in matching the model to data, and in developing the mathematics needed to describe the transport of the drug from nanoparticle to brain tissue. This is joint work with Peter Hinow (U. Wisconsin, Milwaukee), John Reynold and Ian Tucker (U. Otago, Dunedin, NZ).

Ami Radunskaya
Pomona College
Mathematics Department
aer04747@pomona.edu

MS173

Bifurcation Analysis of Calcium Oscillations in the Afferent Arteriole Model of Smooth Muscle Cells

The afferent arteriole (AA) of rat kidney exhibits the myogenic response, in which the vessel constricts in response to an elevation in blood pressure and dilates in response to a pressure reduction. Additionally, the AA exhibits spontaneous oscillations in vascular tone at physiological luminal pressures. These time-periodic oscillations stem from the dynamic exchange of Ca^{2+} between the cytosol and the sarcoplasmic reticulum, coupled to the stimulation of Ca^{2+}-activated potassium and chloride channels, and to the modulation of voltage-gated L-type Ca^{2+} channels. The effects of physiological factors, including blood pressure and vasoacive substances, on AA vasomotion remain to be well characterized. In this paper, we analyze a mathematical model of Ca^{2+} signaling in an AA smooth muscle cell. The model represents detailed transmembrane ionic transport, intracellular Ca^{2+} dynamics as well as kinetics of nitric oxide (NO) and superoxide (O_2^-) formation, diffusion and reaction. NO is an important factor in the maintenance of blood pressure and O_2^- has been shown to contribute significantly to the functional alternations of blood vessels in hypertension. We perform a bifurcation analysis of the model equations to assess the effect of luminal pressure, NO and O_2^- on the behaviors of limit cycle oscillations.

Ning Wei
Duke University
nwei@math.duke.edu

Anita T. Layton
Duke University
Department of Mathematics
alayton@math.duke.edu

MS173

Modelling the Interplay Between Cell Signalling and Cell Mechanics

Protein signalling networks are responsible for regulating the shape and polarity of cells. Rac and Rho are mutually inhibitory signalling proteins that regulate a cell's ability to form protrusions (Rac) and to contract (Rho). As cells change shape, migrate individually, or move as group, they experience forces from their environment and neighbours. These forces are translated into chemical signals that may increase or decrease the activities of Rac and/or Rho. We develop and analyze a nonlinear ODE model for Rac and Rho signalling within a cell and then couple cells mechanically. To explore the interplay between cell mechanics and cell signalling, we couple Rac and Rho signalling to a simple (spring-dashpot) mechanical model of a cell. We discover that feedback between Rac and Rho signalling and cell mechanics can lead to a variety of dynamics. In particular, in a tissue composed of many cells, we observe waves of contraction from one end of the tissue to the other.

Cole Zmurchok
University of British Columbia
zmurchok@math.ubc.ca

MS174

Anomalous Diffusion in Membranes and Cytoplasm of Biological Cells

A surging amount of experimental and simulations studies reveals persistent anomalous diffusion in both cellular membranes and the cytoplasm [M.J. Saxton and K. Jacobsen, 1997; F. Hofling and T. Franosch, 2013]. The anomalous diffusion is observed for micron-sized objects down to labelled single molecules such as green fluorescent proteins [C. Di Rienzo et al., 2014)]. This talk will first present results from large scale computer simulations and stochastic analysis of the motion of lipids and embedded proteins in lipid bilayer model membranes [J.-H. Jeon et al., 2012; J.-H. Jeon et al., 2016)], indicating that increased disorder leads to longer and longer lasting anomalous diffusion. In particular, the motion of lipids and proteins can become non-Gaussian. In the membranes of living cells anomalous diffusion of embedded protein channels can last over several hundreds of seconds [A.V. Weigel et al., 2011]. In particular, this anomalous diffusion can become non-ergodic and exhibit ageing, two topics explained and discussed in this talk [R. Metzler et al., 2014)]. The findings of anomalous diffusion in membranes will be complemented by a brief summary of anomalous diffusion in the cellular cytoplasm, referring to both subdiffusion of passive tracers [J.-H. Jeon et al., 2011; I. Golding and E.C. Cox, 2006; I. Bronstein et al., 2009; M. Weiss et al., 2004] and superdiffusion due to active motion of cells [J.F. Reverey et al., 2015; N. Gal and D. Weihs, 2010].

Ralf Metzler
Inst for Physics & Astronomy
University of Potsdam
rmetzler@uni-potsdam.de

MS174

A Fractional Kinetic Process Describing the Intermediate Time Behaviour of Cellular Flows

This work studies the intermediate time behavior of a small random perturbation of a periodic cellular flow. Our main result shows that on time scales shorter than the diffusive time scale, the limiting behaviour of trajectories that start close enough to cell boundaries is a fractional kinetic process: A Brownian motion time changed by the local time of an independent Brownian motion. Our proof uses the Freidlin-Wentzell framework, and the key step is to establish an analogous averaging principle on shorter time scales. As a consequence of our main theorem, we obtain a homogenization result for the associated advection-diffusion equation. We show that on intermediate time scales the effective equation is a fractional time PDE that arises in modelling anomalous diffusion.

Martin Hairer
The University of Warwick
M.Hairer@Warwick.ac.uk

Gautam Iyer
Carnegie Mellon University
gautam@math.cmu.edu

Leonid Koralov
Princeton University
koralov@Math.Princeton.ED

Alexei Novikov
Penn State University
Mathematics
anovikov@math.psu.edu

Zsolt Pajor-Gyulai
Courant Institute of Mathematical Sciences
New York University
zsolt@cims.nyu.edu

MS174

Anomalous Dispersion of Particles in Steady Two-dimensional Flows

It is well known that anomalous dispersion of particles is possible in chaotic or random flows. Surprisingly, it is possible also in steady spatially-periodic flows in the absence of both Eulerian and Lagrangian chaos, if the flow pattern includes stagnation points or solid obstacles [M.A. Zaks *et al.*, Phys. Rev. Lett. 77 (1996) 4338-4341; M.A. Zaks and A.V. Straube, Phys. Rev. Lett. 89 (2002) 244101]. In this talk, we present a quantitative description of this phenomenon using a special flow construction: flow over the circle mapping with logarithmic and power-law singularities of return time. Analytical estimates, based on computation of partial sums of series and the CTRW approach, match the numerical data from the direct simulation of the flow. The research was supported by Grant 3140-11899 from the German-Israeli Foundation for Scientific Research and Development.

Michael Zaks
Humboldt University of Berlin
zaks@physik.hu-berlin.de

Alexander Nepomnyashchy
Technion
Israel Institute of Technology
nepom@math.technion.ac.il

MS175

Active Matter in Time-Periodic Flows: Swimming with Gradients

In this talk, I will discuss the transport dynamics of active particles (i.e. swimming bacteria) in two-dimensional time-periodic flows using a magneto-hydrodynamic flow cell. This experimental setup allows for the creation of flows of different structures and dynamical properties depending on the arrangement of the underlying magnets and magnitude of forcing. Flow velocity fields are measure using particle tracking methods and used to calculate the flows stretching fields and finite-time Lyapunov exponents (FTLE). The transport of bacteria in this 2D flow is investigated by injecting dilute suspensions of Vibrio cholerae. Surprisingly, we find that activity (or swimming) can hinder overall transport compared to passive particles. While at short times, bacteria tend to align along regions of high stretching, we find that at long times bacteria accumulate near elliptic points of the flow. This accumulation leads to a decrease in overall transport.

Paulo E. Arratia
Mechanical Engineering and Applied Mechanics
University of Pennsylvania, Philadelphia.
parratia@seas.upenn.edu

MS175

Lagrangian Stochastic Prediction and Data Assimilation

We first present differential equations and high-order numerical schemes for predicting the probability of Lagrangian Coherent Structures (LCS) in uncertain flows. We then derive Bayesian Lagrangian data assimilation schemes for the joint inference of structures and fields. Results are extended to Lagrangian-Eulerian Bayesian inference, mutual information, and smoothing. Examples are provided for idealized incompressible fluid and geophysical flows, as well as for realistic data-assimilative multiresolution ocean simulations.

Pierre F. Lermusiaux
MIT
pierrel@mit.edu

Chinmay S. Kulkarni
Massachusetts Institute of Technology
chinmayk@mit.edu

Florian Feppon, Arkopal Dutt
MIT
feppon@mit.edu, arkopal@mit.edu

MS175

Optimizing Vehicle Autonomy in Geophysical

Flows

Autonomous marine vehicles (AMVs) deployed for ocean science and environmental monitoring applications must operate with little to no human supervision for long periods of time. Given their limited energy budgets, it makes sense to consider motion plans that leverage the dynamics of the surrounding flow to minimize the vehicles' energy expenditures. We present recent graph search based methods in computing energy and time optimal paths for AMVs in time independent and time-varying flows. Leveraging our graph search methods, we analyze and relate energy and time optimal paths in deterministic flows with escape trajectories in stochastic flows.

Ani Hsieh
Drexel University
mhsieh1@drexel.edu

Shibabrat Naik
Engineering Science and Mechanics
Virginia Tech
shiba@vt.edu

Dhanushka Kularatne
Drexel University
dnk32@drexel.edu

Subhrajit Bhattacharya
Lehigh University
sub216@lehigh.edu

Eric Forgoston
Montclair State University
Department of Mathematical Sciences
eric.forgoston@montclair.edu

MS175

Adaptive Learning and Prediction of Motion of Controlled Lagrangian Particles

Marine robots can be viewed as a new type of Lagrangian particles with their motion under feedback control. When the controlled speed is relatively weak comparing to the speed of ocean current, the controlled Lagrangian particles will demonstrate complex yet interesting trajectories that can be partially modeled by stochastic systems with unknown input and parameters. This talk will explain the various factors that affect the trajectories. Furthermore, adaptive learning and control methods are applied to reduce the uncertainty in the trajectories. In addition to theoretical analysis, the results are verified through simulation and experimental effort.

Fumin Zhang
School of Electrical and Computer Engineering
Georgia Institute of Technology
fumin@gatech.edu

Sungjin Cho
Georgia Institute of Technology
scho88@gatech.edu

MS176

Mathematical Model of a Network Containing Electrotonic Junctions Between Excitatory Neurons in the Adult Cortex

Synchronization of neurons in the cortex is thought to underlie several cognitive processes such as learning and memory formation. Fitting data from experimental papers, we construct a detailed model with synaptic and electric coupling using a modified version of the Hodgkin-Huxley equations. We use this model to show that a small percentage of excitatory neurons connected via electrical junctions serves to tighten synchrony in a realistic cortical network.

Jennifer Crodelle
Rensselaer Polytechnic Institute
kilej@rpi.edu

Gregor Kovacic
Rensselaer Polytechnic Inst
Dept of Mathematical Sciences
kovacg@rpi.edu

David Cai
New York University
Courant institute
cai@cims.nyu.edu

MS176

Emergence of a Balanced Core Through Dynamical Computation in Inhomogeneous Neuronal Networks

The balance between excitatory and inhibitory current input is crucial for neuronal computation and has been observed in many experiments. Theoretical studies have mainly focused on the analysis of homogeneous networks. However, neuronal networks in the brain are usually inhomogeneous. Here we show that the balanced state can exist even in inhomogeneous neuronal networks and embedded in the original network there is a homogeneous-like core that underlies origin of the balanced state.

Qinglong Gu
Shanghai Jiao Tong University
gu.qinglong@outlook.com

MS176

Neuronal Network Reconstruction by Transfer Entropy

We apply low order and pairwise Transfer entropy to reconstruct the structural connectivity of neuronal networks based on only the spike trains. In this work, we use a current-based, integrate-and-fire network and address the issue of why the reconstruction can be successfully achieved. We also obtain a quadratic relationship between the TE and the coupling strength and establish a direct link between the causal and structural connectivity in the network.

Zhongqi Tian
New York University
13429237441@sjtu.edu.cn

MS176

Spike Triggered Regression on Neuronal Network Reconstruction

We propose a spike-triggered regression (STR) method to accurately reconstruct the network connectivity of a nonlinear integrate-and-fire (I&F) neuronal network. The basic idea of our method is to capture the subthreshold voltage response to a presynaptic spike through linear regression. Through numerical simulations, we demonstrate that, by using relatively short-time recordings, the I&F neuronal network connectivity can be well reconstructed using our STR method.

Yaoyu Zhang
New York University
yaoyu@cims.nyu.edu

MS177

Modeling and Estimation of Dynamical Variables in a Cardiac Cell Model

Cellular dynamical variables, such as ionic concentrations and gating states, play an important role in the formation of cardiac arrhythmias. Since these quantities can be difficult to measure, a Kalman filtering approach was tested on dynamical model of a myocyte, the Luo-Rudy dynamic model, and it was shown that cellular variables can be reconstructed based on simulated measurements of membrane potential. The observability of the system was characterized under a range of conditions.

Laura Munoz
Rochester Institute of Technology
School of Mathematical Sciences
lmmsma@rit.edu

Claire Charron, Kalyan Pusarla
Rochester Institute of Technology
claire@mail.rit.edu, kp9211@rit.edu

MS177

Wave Control by Cooperative Excitation of Cardiac Tissue

Rotating excitation waves and electrical turbulencein cardiac tissue have been associated witharrhythmias like the life-threatening ventricular fibrillation. The application of an electrical shock (defibrillation) is an effective therapy, as it globally excites the tissue resulting in termination of all excitation waves, but also causes severe side effects. Recent experimental studies have shown that a sequence of electrical pulses is able terminate fibrillation more gently than a single pulse. Only tissue at major conduction heterogeneities, such as large coronary arteries, may be activated by each of these very weak pulses. Therefore, global tissue activation and wave termination originates from few localized activation sites. In order to decipher the interplay of the individual pulses, we performed extensive simulations of cardiac tissue perforated by blood vessels and tested a variety of cellular models. For models exhibiting a dominant excitation period during fibrillation, the pulses appear to be highly cooperative if the period between these pulses matches the dominant period. These findings are elucidated by the analysis of the dynamical variables, such as the fraction of excited tissue and the number of phase defects, both during the state of electrical turbulence and during cooperative excitation. Moreover, we propose a simple stochastic model which integrates our results in an intuitive way.

Thomas Niedermayer
Research Group Complex Systems in Biophysics and Medicine
Physikalisch-Technische Bundesanstalt (PTB)
niedermayerthomas@gmail.com

Pavel Buran
Physikalisch-Technische Bundesanstalt (PTB)
pavel.buran@ptb.de

Sergio Alonso
UPC, Barcelona
s.alonso@upc.edu

Markus Baer
Physikalisch-Technische Bundesanstalt (PTB)
markus.baer@ptb.de

MS177

New Insights into the Termination of Unpinned Spiral Waves Using Low-Energy Electric Field Pulses

Successful termination of rapid cardiac arrhythmias using low-energy, electric-field based shocks requires a new understanding of how action potential waves launched by the applied electric field pulses interact with the rotating waves that are responsible for the arrhythmia. In this talk, we present our findings on (1) how waves launched from obstacles inherent in cardiac tissue can merge with the rotating waves to create new waves that terminate upon interaction with the boundaries, and (2) how plane waves launched from boundaries can merge with rotating waves in three dimensions to form waves with C-shaped filaments that then shrink and disappear. With respect to the first mechanism, we will also suggest what field strengths and stimulus timings are most likely to terminate a rotating wave, and discuss an ECG-based method might be able to determine the location and phase of the rotating wave, which is needed to determine the appropriate stimulus timing. For the second mechanism, we will also discuss the importance of the shape of the boundary as a factor in determining whether the C-shaped filament will shrink and disappear, or revert back to an I-shaped filament that persists indefinitely.

Niels Otani
Rochester Institute of Technology
nfosma@rit.edu

Valentin Krinski
Max Planck Institute for Dynamics and Self-Organization
valentin.krinsky@ds.mpg.de

Shuyue Han, Kayleigh Wheeler
Rochester Institute of Technology
sxh8216@rit.edu, kmw7139@rit.edu

Stefan Luther
Max Planck Institute for Dynamics and Self-Organization
Research Group Biomedical Physics
stefan.luther@ds.mpg.de

MS177

Controlling the Dynamics of Cardiac Tissue During Ventricular Fibrillation

Ventricular fibrillation is a lethal condition of the heart which is still not well understood and medicine lacks a suitable treatment. The irregular and fast activation patterns during ventricular fibrillation make it hard to find efficient methods to control the dynamics of the myocardium. In contrast, e.g. monomorphic ventricular tachycardia can often be terminated by local stimulation with a train of uniform electric pulses. While such a local stimulation has a very limited region of influence in ventricular fibrillation, we demonstrate how fast trains of electric far field pulses modify the properties of the dynamics in heterogeneous cardiac tissue and may facilitate efficient termination of ventricular fibrillation.

Henrik tom Woerden
Max Planck Institute for Dynamics and Self-Organization
henrik.tom-woerden@ds.mpg.de

MS178

Modeling Differential Transmission Characteristics of Whitefly-Transmitted Cassava Viruses

The whitefly, Bemisia tabaci, is one of the most economically important insect vectors of plant viruses. It transmits over 200 viruses through either semi-persistent or persistent mechanisms. Cassava mosaic geminiviruses and Cassava brown streak viruses have been associated with region-wide spread of a dual pandemic of cassava mosaic disease (CMD) and cassava brown streak disease (CBSD). We formulate a deterministic compartmental model for host-vector dynamics. Our simulations show that these models not only fit the field data well, with biologically meaningful parameter estimates, but additionally they also capture the differences between the two types of viral infections: CMD and CBSD.

Ariel Cintron-Arias
Department of Mathematics and Statistics
East Tennessee State University
cintronarias@etsu.edu

MS178

Comparative Estimation of Parameters for Dengue and Chikungunya in Costa Rica from Weekly Reported Data

Dengue virus has been a cause of major public health concern in Costa Rica. In 2014 the Chikungunya virus was introduced. We look at the 2015-2016 dengue and chikungunya outbreaks in order to establish a comparison using weekly longitudinal data. A nonlinear differential equation single-outbreak model is validated against the aggregate data. We estimate epidemic model parameters, including the basic reproductive number, R_0, and explore the impact of undiagnosed cases.

Fabio Sanchez
University of Costa Rica
fsanchez1019@gmail.com

MS178

Using a Mathematical Model and Likelihood Methods to Assess Contagion in Mass Killings and School Shootings

In recent years there have been several high-profile public mass killings in the US, increasing societal focus on the persistent problem of firearm violence in American society. Here, I present the results of our recent analysis of data related to US mass shootings (three or more people shot, not necessarily killed), school shootings, and mass killings (four or more people killed). We examine the data using a mathematical model of contagion. Using likelihood methods, we assess the probability that the null hypothesis (no contagion) is true, while accounting for over-dispersion in the data. Our analysis finds that some, but not all, of these tragedies do indeed appear to be significantly contagious, and media attention appears to play a key role in these dynamics.

Sherry Towers
Mathematical and Computational Modeling Sciences Center, ASU
smtowers@asu.edu

MS178

Extra High-Dimensional Linear ODE Model Selection and Parameter Estimation: A Matrix-Based Approach

Ordinary differential equations (ODEs) are widely used to model the dynamic behavior of a complex system. Parameter estimation and variable selection for a Big System with high-dimensional linear ODEs are very challenging due to the difficulty of nonlinear optimization problems with an extra-high parameter space. In this article, we develop a parameter estimation and variable selection method based on the ideas of similarity transformation and separable least squares (SLS). Simulation studies demonstrate that the proposed matrix-based SLS method could be used to estimate the coefficient matrix more accurately and perform variable selection for a linear ODE system with thousands of dimensions and millions of parameters much better compared to the direct least squares (LS) method and existing vector-based two-stage method. We apply our new method to two application data sets: a yeast cell cycle gene expression data set with 30 dimensions and 930 unknown parameters; and the Standard & Poor 1500 index stock price data with 1250 dimensions and 1,563,750 unknown parameters.

Hulin Wu
Department of Biostatistics
University of Texas Health Science Center at Houston
hulin.wu@uth.tmc.edu

MS179

Topological Existence of Periodic Orbits in a Two-Center Symmetric Pair Problem

The Two-Center Symmetric Pair Problem, derived from the Rhomboidal Symmetric-Mass problem by fixing one symmetric pair, limits, as the mass of the non-fixed symmetric pair goes to zero, to the integrable Euler Two-Center Problem (with the centers having equal mass). Standard KAM Theory indicates that many of the quasi-periodic orbits found in the integrable limit case persist for small values of the mass of the non-fixed symmetric pair. Through topological methods, we investigate the existence of several periodic orbits in the Two-Center Symmetric Pair Problem with and without collisions when the mass of the symmetric pair is not necessarily close to zero.

Lennard F. Bakker, Mitchell Sailsbery
Brigham Young University
bakker@math.byu.edu, mitchell.sailsbery@gmail.com

MS179

High Energy Scattering: Orbit Structure

We report on the motivation and results of "Lagrangian Relations and Linear Point Billiards" (arXiv:1606.01420) joint with Knauf and Fejoz. Motivated by the high-energy limit of the N-body problem we construct non-deterministic billiard process. The billiard table is the complement of a finite collection of linear subspaces within a Euclidean vector space. A trajectory is a constant speed polygonal curve with vertices on the subspaces and change of direction upon hitting a subspace governed by 'conservation of momentum' (mirror reflection). The itinerary of a trajectory is the list of subspaces it hits, in order. Two basic questions are: (A) Are itineraries finite? (B) What is the structure of the space of all trajectories having a fixed itinerary? In a beautiful series of papers Burago-Ferleger-Kononenko [BFK] answered (A) affirmatively by using non-smooth metric geometry ideas and the notion of a Hadamard space. We answer (B) by proving that this space of trajectories is diffeomorphic to a Lagrangian relation on the space of lines in the Euclidean space. Our methods combine those of BFK with the notion of a generating family for a Lagrangian relation.

Richard Montgomery
University of California at Santa Cruz
rmont@ucsc.edu

MS179

Towards a Restricted N-Body Stability Result

The rhomboidal four-body orbit and Broucke's isosceles triangle orbit are two examples of periodic Newtonian n-body orbits featuring regularizable binary collisions. These periodic orbits can still be found for each as a certain mass parameter is varied between them. In my talk, I will discuss how the limiting cases for both orbits is the same (in an appropriate sense), and present stability results for both orbits as this parameter varies, suggesting the stability of their common limit.

Skyler Simmons
Southern Utah University
xinkaisen@gmail.com

MS179

Remarks on the N-Body Dynamics on Surfaces of Revolution

We explore the dynamics of N mass points constrained to move on a surface of revolution and with some binary potential interaction. We discuss symmetries and determine certain invariant manifolds. We also show that the equivalent of Saari's conjecture for such motions fails. Further, we define homographic motions to be those for which the configuration formed by the bodies is planar, orthogonal to the axis of revolution and remains self-similar in the ambient space. For equal masses, using discrete reduction, we show that such motions form a two-degree of freedom mechanical system with symmetry for which one may provide a complete topological description of its phase space. We also comment on the role of Gaussian curvature on the stability of regular N-gon relative equilibria.

Cristina Stoica
Department of Mathematics
Wilfrid Laurier University
cstoica@wlu.ca

PP1

Entropy and Dynamical Systems

This paper will discuss different definitions of entropy and their relationship to dynamical systems. A review of the literature indicates that there are many open questions concerning the relationships among the myriad definitions of entropy. Our approach focuses on the Hamiltonian dynamical system foundation of the statistical thermodynamics definition of entropy. Entropy has played a role in many areas of physics from the 1850's when Clausius coined the term to indicate a dissipation of energy, and has continued on in the later part of that century with the work of Boltzmann, Gibbs and Planck. Information theory developed by Shannon, used the Boltzmann definition of entropy. More recently a topological entropy is used as a measure of sensitivity in dynamical systems. We plan to establish rigorous connections among several of the most important definitions of entropy. These definitions include the classical thermodynamics, statistical entropy to topological entropy, with a common dynamical systems thread. The results of our approach will then be applied to some physical models.

Raymond Addabbo
Vaughn College of Aeronautica and Technology
Raymond.addabbo@vaughn.edu

Denis Blackmore
New Jersey Institute of Technology
denis.l.blackmore@njit.edu

PP1

Neuronal Motifs - Multistability Using Hybrid Computational Approaches

Large scale analysis of the dynamical behavior of Central Pattern Generators (CPGs) formed by neuronal networks of even small sizes is computationally intensive and grows exponentially with network size. We have developed a suite of tools to exhaustively study the behavior of such networks on modern GPGPU accelerators using the directive based approach of OpenAcc. We also achieve parallelization across clusters of such machines using OpenMPI. Directive based approaches simplify the task of porting serial code onto GPUs, without the necessity for expertise in lower level approaches to GPU programming, such as CUDA and OpenCL. 3-cell neuronal CPGs have been explored previously using various GPGPU tools. As motifs form the building blocks of larger networks, we have employed our framework to study 4-cell CPGS and two connected 3-cell motifs. We discuss the performance improvements achieved using this framework and present some of our results.

Sunitha Basodi, Krishna Pusuluri
Georgia State University
sunitha.basodi@gmail.com, kpusuluri1@student.gsu.edu

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

PP1

Computing the Optimal Path in Stochastic Dynamical Systems

In stochastic systems, one is often interested in finding the optimal path that maximizes the probability of escape from a metastable state or of switching between metastable states. Even for simple systems, it may be impossible to find an analytic form of the optimal path, and in high-dimensional systems, this is almost always the case. We have formulated a constructive methodology that is used to compute the optimal path numerically. The method utilizes finite-time Lyapunov exponents, statistical selection criteria, and a Newton-based iterative minimizing scheme, and can be used for high-dimensional systems where other methods are known to fail. We demonstrate the method with a variety of examples.

Martha Bauver
Montclair State University
bauverm10@gmail.com

Lora Billings, Eric Forgoston
Montclair State University
Department of Mathematical Sciences
billingsl@mail.montclair.edu,
eric.forgoston@montclair.edu

PP1

Gabaergic Synaptic Mechanisms in Information Transmission

In this work we analyze a mathematical model (a map parameterized from experimental data) to explore information transmission at GABAergic PV basket cell- pyramidal cell synapses in mouse hippocampus. Specifically, we quantify the information contained in the amplitude of the postsynaptic response induced by Poisson spike trains in deterministic and stochastic models of the synapse. In the stochastic model, the additional variability predictably reduces the overall information transmission compared to the deterministic model. However, we found that there is a peak in the information transmission around 2 Hz, in the theta frequency range. With an information efficacy measure we confirmed that the action of the map is not uniform over all frequencies, it has the greatest effect in reducing information transmission at very low and high frequencies. We also show that calcium concentration in the model follows a gamma distribution with shape and scale parameters that depend on mean frequency rate and calcium decay time constant. In the special case when the calcium decay time is notably smaller than the interspike interval, the postsynaptic response follows beta distribution with parameters that depend on mean frequency rate and minimum recovery rate of the synapse.

Elham Bayat-Mokhtari
University of Montana - Missoula
elham.bayatmokhtari@umconnect.umt.edu

Emily F. Stone
Dept. of Mathematical Sciences
The University of Montana
stone@mso.umt.edu

PP1

Contrasting Epidemic Control in Ordinary and Delay Differential Equations

Modeling the spread of epidemics has been a useful tool in predicting the outcome of an infectious disease. Our focus is how to model the distributions of exposed and infectious time periods and how applying a disease control strategy affects the models accuracy. While ordinary differential equations are widely used for their simplicity, they incorporate an exponential distribution for time spent exposed or infectious. This allows a high probability of unrealistically short exposed and infectious time periods. We propose that extra care must be taken when applying intervention methods such as quarantine, hospitalization, or vaccination to basic models in order to avoid inaccurate predictions. Delay differential equations, which use fixed exposed and infectious periods, can provide better realism but are more difficult to use and analyze. We introduce a multi-infected compartment model to interpolate between the ODE model and the DDE model in order to investigate the effect a time delay will have on the dynamics of the system when an intervention method is also included. Using steady state stability and bifurcation analysis, this project will provide guidelines for when simpler infectious disease models can be used or more realistic time periods must be incorporated.

Adrienna Bingham
The College of William and Mary
anbingham@email.wm.edu

Leah Shaw
College of William and Mary
lbshaw@wm.edu

PP1

Chaotic Advection in the Alboran Sea: Lagrangian Analysis of Transport Processes in and Out of the Western Alboran Gyre

The Alboran Sea, east of the Strait of Gibraltar, is where Atlantic water enters the Mediterranean as the Atlantic Jet, AJ. The AJ interacts with coastal recirculations, notably the Western Alboran Gyre (WAG) a persistent anticyclonic mesoscale eddy. Past studies of local Finite-Size Lyapunov Exponents (e.g. Sayol et. al, Sea surface transport in the Western Mediterranean Sea: A Lagrangian perspective", J. Geophys. Res.: Oceans 118.12 2013) highlight the periphery of the WAG, implying that it has chaotic flow motion characterized by exponential stretching and folding of fluid parcels. Our work examines the near-surface exchange between the AJ and WAG in a high-resolution regional run of the MIT general circulation model (Marshall et al., Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling", J. Geophys. Res., 102(C3) 1997). This model solves the Boussinesq Navier-Stokes equations for an incompressible fluid with finite-volume spatial discretization on a curvilinear grid. We use Lagrangian methods from dynamical systems, manifolds and lobe analysis, to define the moving WAG boundary and quantify advective transport across it. We identify the stirring region, where exchanges with the AJ occur, and the WAG core, where they do not. Qualifying transport across the boundary of this modeled mesoscale eddy may contribute to the design of observational campaigns.

Genevieve Brett
Massachusetts Institute of Technology
Woods Hole Oceanographic Institution
gbrett@mit.edu

Larry Pratt
Woods Hole Oceanographic Inst.
lpratt@whoi.edu

Irina Rypina
Woods Hole Oceanographic Institution

irypina@whoi.edu

PP1

A Novel Speech-Based Diagnostic Test for Parkinson's Disease Integrating Machine Learning with Application Development for Cloud Deployment

Parkinson's disease remains one of the most poorly diagnosed neurological conditions despite the critical need of early diagnosis for effective management and treatment. This work presents a new method of diagnosing Parkinsons disease and accompanying scalable web and mobile applications towards the goal of employing this diagnostic test on the cloud. This method provides a more simple, inexpensive, and time-effective approach than traditional diagnosis strategies by requiring the patient to only speak into a microphone attached to their computer or mobile device before providing a highly accurate diagnosis within seconds. This work employs speech processing algorithms, an artificial neural network for machine learning, and an application framework with a user-friendly interface that packages the speech test and diagnosis results for easy access by patients and physicians. This test was specifically designed for rapid in-home Parkinsons testing, a capability that is currently not offered by any existing tests available on the market. The diagnosis test developed here was tested with actual patient data and was shown to be 96.55% accurate. The results of this research thus take a significant step towards building the first globally available speech test for the diagnosis of Parkinson's disease.

Pooja Chandrashekar
Harvard University
pchandrashekar@college.harvard.edu

PP1

Synchronization of Electrically Coupled Hybrid Neuron Models

Electrical coupling between neurons is typically assumed to synchronize network activity. In the inferior olive and many other brain regions, the coupled cells have intrinsic resonant properties that may complicate this simple picture. We explore this issue by studying synchronization in small networks of electrically coupled resonate-and-fire neurons, using the theory of weakly coupled oscillators. With our choice of a solvable minimal model, the weak coupling approach permits an analytical model reduction to single-variable phase oscillators, from which properties such as the existence and robustness of synchronized solutions are easily inferred. Our study has two main results. First, we develop a broadly applicable extension of the phase reduction approach to hybrid models with discontinuous dynamics. Second, we apply our phase reduction method to the resonate-and-fire model, uncovering subtle effects on synchronization. Specifically, we show that an even component arises in the phase interaction function due to "reset-induced shear," a geometric feature of threshold crossing in two or more dimensions. Although often overlooked because it has no effect on mean-field coupled oscillator networks or coupled pairs, we show that this even component in general has complex effects that can either support or oppose network synchrony.

Thomas Chartrand
UC Davis
tmchartrand@gmail.com

Timothy Lewis
Department of Mathematics
University of California, Davis
tjlewis@ucdavis.edu

Mark Goldman
UC Davis
msgoldman (at) ucdavis (dot) edu

PP1

Hybrid Statistical and Mechanistic Model Guides Mobile Health Intervention for Chronic Pain

Patients with sickle cell disease (SCD) often suffer from daily chronic pain, traditionally managed at home using physician-guided recommendations. Recently, physicians have streamlined their recommendations by utilizing mobile health applications (mHealth). These applications collect objective patient data, such as heart rate and temperature, and subjective information, such as perceived pain and nausea, with the goal of giving immediate personalized pain interventions. In order to balance pain with the number of opioid and non-opioid drugs taken, we use a hybrid statistical-dynamical systems model of perceived pain that predicts a time series of pain levels for a variety of interventions (including drugs). This will assist physicians in offering optimal pain interventions remotely.

Sara Clifton
Northwestern University, USA
sclifton@u.northwestern.edu

Daniel Abrams
Northwestern University
dmabrams@u.northwestern.edu

Chaeryon Kang
University of Pittsburgh
crkang@pitt.edu

Jessica Li
University of Californina Los Angeles
jli@stat.ucla.edu

Qi Long
University of Pennsylvania
qlong@mail.med.upenn.edu

Nirmish Shah
Duke University
nirmish.shah@duke.edu

PP1

Bifurcation Theory and Phase-Lag Variance in 3-Node Neural Networks

Central pattern generators (CPGs) are functional units commonly tied to neurons coupled in half-center oscillators (HCO). We examine these in 3-cell motifs, often forming centers for larger networks, and explore connectivity giving rise to network bursting. We show that inhibitory Fitzhugh-Nagumo-type (FN) networks can produce a range of phase-locked states: pacemakers (Pace), traveling waves (Wave), or peristaltic rhythms with recurrent phase-varying lags (River). We replicate and build on results using Hodgkin-Huxley-type models, promoting simplified modeling of biologically plausible CPG circuits. Our reduction maintains all generic behaviors and permits a broader exploration of the network state space, aiding in the search of biologically relevant parameters resulting in the robustness and stability observed in nature. We do this with a particular eye for multi-stable rhythms, in which a single biologically relevant parameter induces rhythm changes in otherwise robustly oscillatory networks.

Jarod Collens
Georgia State University
Neuroscience Institute and Mathematics Department
jcollens1@student.gsu.edu

Deniz Alacam
Georgia State University
Mathematics Department
dalacam1@student.gsu.edu

Aaron Kelly
Georgia State University
Neuroscience Institute
aarnkelley@gmail.com

Drake Knapper
Georgia State University
dknapper1@student.gsu.edu

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

PP1

On a Mathematical Model for the Multiplex Line Graph

Multilayer and multiplex networks explicitly incorporate multiple channels of connectivity in a system and constitute the natural mathematical setting for representing systems whose elements are interconnected through different kinds of connections (or levels); thus each level (channel, relationship, activity, category) is represented by a layer containing all the elements that have connections at that particular level. Notice that two elements may belong to two different layers if they are connected at more than one level (family level, or work level or friendship and vicinity levels etc.). The concept of line graph naturally arises when edges in a specific network (a graph with a huge number of nodes and edges) are given more importance than nodes. Recall that the line graph $L(G)$ of an undirected graph G is another graph whose nodes are the edges of G, and two nodes of $L(G)$ are adjacent if the corresponding edges in G share a common node. Surprisingly line graphs have only been considered in a reduced number of studies an applications that involve networks. In the case of multiplex networks even the concept of line graph has not been properly addressed. In fact the richer structure of a multiplex network makes it difficult to come up with a sound definition. Thus in our poster we will analyze some different approaches to the definition of the line graph associated to a multiplex network as well as some potential applications.

Regino Criado, Julio Flores, Alejandro García del Amo
Universidad Rey Juan Carlos
regino.criado@urjc.es, julio.flores@urjc.es,
alejandro.garciadelamo@urjc.es

Miguel Romance
Centre for Biomedical Technology (CTB)
Technical University of Madrid, Pozuelo de Alarcón, Madrid
miguel.romance@gmail.com

Eva Barrena
Universidad de Granada
ebarrena@us.es

Juan A. Mesa
Department of Applied Mathematics II
Universidad de Sevilla
jmesa@us.es

PP1

A Robust Torus Used to Control Chaos in Wave-Particle Interactions

We analyze the dynamics of relativistic particles moving in a uniform magnetic field and interacting with a stationary electrostatic wave. When particles and wave are in resonance, the wave transfers a great amount of energy to the particles and they are accelerated. By increasing the amplitude of the wave, we increase the amount of energy transferred to the particles. However, there is a limit to this process. For large values of the wave amplitude, the system becomes chaotic and it is no longer possible to regularly accelerate the particles. In this presentation, we create a robust torus in the phase space of the system. When the robust torus is properly adjusted, we show that it may be used to control chaos in the system and to restore the process of regular particle acceleration from low initial energies.

Meirielen C. De Sousa
Instituto de Física, Universidade de São Paulo, Brazil
meirielenso@gmail.com

Ibere L. Caldas
Institute of Physics
University of Sao Paulo
ibere@if.usp.br

PP1

Lyapunov-Type Inequalities for α-Th Order Fractional Differential Equations with $2 < \alpha \leq 3$ and Fractional Boundary Conditions

We study linear fractional boundary value problems consisting of an α-th order Riemann-Liouville fractional differential equation with $2 < \alpha \leq 3$ and certain fractional boundary conditions. We derive several Lyapunov-type Inequalities and apply them to establish nonexistence, uniqueness, and existence-uniqueness for solutions of related homogeneous and nonhomogeneous linear fractional boundary value problems. As a special case, our work covers and improves some existing results for the third-order linear boundary value problems.

Sougata Dhar, Qingkai Kong
Northern Illinois University
sdhar@niu.edu, qkong@niu.edu

PP1

A Mathematical Model of Parallel Quorum Sensing

Quorum Sensing (QS) is a cell-cell communication process that uses signal-receptor binding to regulate genes based on cell density, resulting in collective behaviors such as biofilm formation, bioluminescence and stress response. In

certain bacterial species such as V. harvey, several parallel QS signaling pathways drive a single phosphorylation-dephosphorylation cycle (PdPC), which in turn regulates QS target genes. We propose a coupled cell model for parallel QS in V. Harveyi, and show how different combinations of parallel signals can be used by the bacteria to gain information on their social and physical environments.

Gaoyang Fan
University of Utah, Department of Mathematics
gfan@math.utah.edu

Paul C. Bressloff
University of Utah
Department of Mathematics
bressloff@math.utah.edu

PP1

Computing Stable Manifolds of a Saddle Slow Manifold

The behaviour of systems with fast and slow time scales is organised by families of locally invariant slow manifolds. Slow manifolds are characterised by slow time scale dynamics and act as separatrices between different episodes of fast time scale behaviour. There are well-established numerical methods for the approximation of attracting and repelling slow manifolds. On the other hand, there are hardly any methods for computing saddle slow manifolds, which are typical in higher dimensions. A saddle-type slow manifold has associated stable and unstable manifolds that act as attractors and repellers, respectively. These (un)stable manifolds contain both fast and slow time-scale dynamics, which makes them challenging to compute. Based on the theory of nonautonomous systems, we give a precise definition for the stable manifold of a saddle slow manifold and design an algorithm to compute it; our computational method is formulated as a two-point boundary value problem and uses pseudo-arclength continuation with AUTO. In a different parameter regime, the saddle slow manifold contains a saddle equilibrium point and its stable manifold is equal to the global stable manifold of the saddle point. We compare our approximation of the stable manifold of a saddle slow manifold with that as the (global) stable manifold of the saddle equilibrium for which numerical methods are well established.

Saeed Farjami
The University of Auckland
s.farjami@auckland.ac.nz

Hinke M. Osinga
University of Auckland
Department of Mathematics
H.M.Osinga@auckland.ac.nz

Vivien Kirk
University of Auckland
v.kirk@auckland.ac.nz

PP1

Stability of Vortex Solitons for Even-Dimensional Focusing NLS

We consider the nonlinear Schrödinger equation in even space dimension

$$iu_t + \triangle u + |u|^{p-1}u = 0,\ x \in \mathbb{R}^{2n},\ t > 0$$

and study the existence and stability of standing wave solutions of the form

$$e^{iwt} e^{i\sum_{k=1}^{n} m_k\theta_k} \phi_w(r_1, r_2, \cdots, r_n),$$

where (r_k, θ_k) are polar coordinates in $\mathbb{R}^2$ and $m_k \in \mathbb{N}\cup\{0\}$, $k = 1, 2\cdots, n$. We show the existence of such solutions as minimizers of a constrained functional and conclude from there that such standing waves are stable if $1 < p < 1+2/n$.

Wen Feng, Milena Stanislavova
University of Kansas
w262f820@ku.edu, stanis@ku.edu

PP1

Bifurcation Analysis of a Central Pattern Generator Microcircuit in the Xenopus Tadpole Spinal Cord

We present the study of a minimal locomotion-generating microcircuit in the Xenopus tadpole spinal cord. We use experimental data of the identified key neurons that are active during swimming and build a minimal network of 4 spiking neurons and 6 synapses that can reproduce swimming activity. The microcircuit reduces the complexity of the complete spinal cord network to a system of 34 delayed differential equations with parameters that fit experimental data. Despite the reduction in complexity the system can exhibit a range of possible activity patterns, suggesting that this microcircuit could play a fundamental role in other behaviors of the animal. We use numerical continuation to compute the bifurcation diagram of this dynamical system, and find regions in the parameter space corresponding to multi-stability where the swimming and left-right synchrony limit cycles coexists. This can explain the occasional synchrony bouts observed from single cell recordings during swimming.

Andrea Ferrario, Roman M. Borisyuk, Robert Merrison-Hort
School of Computing, Electronics and Math
Plymouth University
andrea.ferrario@plymouth.ac.uk,
r.borisyuk@plymouth.ac.uk,
robert.merrison@postgrad.plymouth.ac.uk

PP1

Hiding the Squid

Cephalopods employ their chromomorphic skins for rapid and versatile active camouflage and signalling effects. This is achieved using dense networks of pigmented, muscle-driven chromatophore cells which are neurally stimulated to actuate and affect local skin colouring. This chromatophore system enables cephalopods to adopt a variety of dynamic and complex skin patterns, most commonly used to blend into the environment or to communicate with other animals. An artificial skin that can mimic such pattern generation has the potential to improve understanding of the chromatophore system and produce a host of novel and compliant devices such as cloaking suits and dynamic illuminated clothing. In this talk we discuss the design, mathematical modelling and analysis of a dynamic biomimetic pattern generation system using bioinspired artificial chromatophores. We implement the system in artificial skin made from electroactive dielectric elastomer: a soft smart material that we show can be effective at mimicking the actuation of biological chromatophores. By modelling sets of artificial chromatophores in arrays of cells, equipped with a nonlinear local feedback mechanism, we explore the capability of the system to generate a variety of global dynamic patterns. We show that by appropriate choice of the feedback rules it is possible to mimic complex dynamic patterning seen in cephalopods, such as the passing cloud display.

Aaron Fishman, Jonathan Rossiter
University of Bristol
aaron.fishman@bristol.ac.uk,
jonathan.rossiter@bristol.ac.uk

Martin Homer
University of Bristol
Department of Engineering Mathematics
martin.homer@bristol.ac.uk

PP1

Cascades of Saddle Periodic Orbits and Their Manifolds Close to a Homoclinic Flip Bifurcation.

Studying the qualitative dynamics of a system of differential equations is an important tool for comprehending the behaviour of natural phenomena. Of particular importance are the creation and disappearance of saddle periodic orbits and the interaction of their associated stable and unstable manifolds with other invariant objects in phase space; such that they can bound and destroy basins of attraction. We study a phenomenon in three-dimensional vector fields, called a homoclinic flip bifurcation, that is characterised by a change in the associated stable (or unstable) manifolds of a real saddle equilibrium from being orientable to non-orientable. The homoclinic flip bifurcation is a codimension-two phenomenon and, under certain conditions, it leads to cascades of period-doubling and homoclinic bifurcations curves in parameter plane; this particular homoclinic flip bifurcation is known as case **C**. We are interested in understanding how the global invariant manifolds associated with a homoclinic flip bifurcation of case **C** interact and what this means for the overall dynamics. The cascades of period-doubling and homoclinic bifurcations create saddle periodic orbits with manifolds that can also be orientable or non-orientable, and their interaction may lead to regions in parameters plane with horseshoe dynamics and chaotic attractors. In our study the invariant manifolds are computed via the continuation of solutions of two-point boundary value problems.

Andrus A. Giraldo
Phd student at the University of Auckland
agir284@aucklanduni.ac.nz

Bernd Krauskopf, Hinke M. Osinga
University of Auckland
Department of Mathematics
b.krauskopf@auckland.ac.nz, H.M.Osinga@auckland.ac.nz

PP1

Parameterization Method for Parabolic Pdes

We consider the problem of computing unstable manifolds for equilibrium solutions of parabolic PDEs posed on irregular spatial domains. Our approach is based on the parameterization method, a general functional analytic framework for studying invariant manifolds of dynamical systems. The method leads to an infinitesimal invariance equation describing the unstable manifold, which we solve recursively via power matching scheme. The recursive scheme leads to linear homological equations for the jets of the manifold which, along with equilibrium and eigenvalue/eigenfuntion problems, we solve using finite element methods. One feature of the method is that we recover the dynamics on the manifold in addition to its embedding. We implement the method for some example problems on various two dimensional domains.

Jorge L. Gonzalez
Florida Atlantic University
jorgegonzale2013@fau.edu

Jason Mireles-James
Departement of Mathematics
Florida Atlantic University
jmirelesjames@fau.edu

Necibe Tuncer
Florida Atlantic University
ntuncer@fau.edu

PP1

Diffusion and Drift in Volume-Preserving Maps

Nearly integrable volume-preserving maps and incompressible flows have many invariant tori on which the dynamics is quasiperiodic in the angle variables. There are also chaotic orbits in regions between tori. Although invariant tori are barriers to chaotic transport for systems with a single action, they are not for systems with multiple actions. When the nearly integrable dynamics are also symplectic or Hamiltonian, the famous theorem of Nekhoroshev guarantees that this action instability can only occur on exponentially long time scales. We study the lack of Nekhoroshev stability in general volume-preserving maps. We find a reduced model for action drift in low-rank resonances and provide supporting numerical results for some two degree-of-freedom symplectic maps and their closely related volume-preserving counterparts.

Nathan Guillery
University of Colorado - Boulder
Applied Math
nathan.guillery@colorado.edu

James D. Meiss
University of Colorado
Dept of Applied Mathematics
jdm@colorado.edu

PP1

Streamwise Localization of Traveling Wave Solutions in Channel Flow

Channel flow of an incompressible fluid at Reynolds numbers above 2400 possesses a number of different spatially localized solutions which approach the laminar flow far upstream and downstream. We use one such relative time-periodic solution that corresponds to a spatially localized version of a Tollmien-Schlichting wave to illustrate how the upstream and downstream asymptotics can be computed analytically. In particular, we show that for these spanwise uniform states the asymptotics predict exponential localization that has been observed for numerically computed solutions of several canonical shear flows but never properly understood theoretically.

Daniel Gurevich, Joshua Barnett
School of Physics
Georgia Institute of Technology
dgurevich6@gatech.edu, jbarnett8@gatech.edu

Roman Grigoriev
Georgia Institute of Technology
Center for Nonlinear Science & School of Physics
roman.grigoriev@physics.gatech.edu

PP1

Dynamics of Delay Logistic Difference Equation in the Complex Plane

The dynamics of the delay logistic equation with complex parameters and arbitrary complex initial conditions is investigated. The analysis of the local stability of this difference equation has been carried out. We further exhibit several interesting characteristics of the solutions of this equation, using computations, which does not arise when we consider the same equation with positive real parameters and initial conditions. Some of the interesting observations led us to pose some open problems and conjectures regarding chaotic and higher order periodic solutions and global asymptotic convergence of the delay logistic equation. It is our hope that these observations of this complex difference equation would certainly be an interesting addition to the present art of research in rational difference equations in understanding the behaviour in the complex domain.

Sk Sarif Hassan
Dept. of Mathematics, UPES, Dehradun, India
?Department of Mathematics
s.hassan@ddn.upes.ac.in

PP1

Beyond Ensemble Averaging in Turbulent Combustion

Transient combustion processes constitute important flow problems for many practical applications (for example high-altitude relight, ignition in internal combustion engines, unstart in scramjets). While classical turbulent combustion models are reasonably accurate for predicting "average" behavior of systems, their usefulness in capturing low frequency but consequently events is questionable. For such problems, it is recognized that multiple individual trajectories should be analyzed. In engineering problems, the trajectory variability stems from lack of knowledge of initial conditions, model approximations, but also external forcing that can be used to drive the solution in certain portions of the attractor. A dynamical system approach is used along with the Lyapunov theory for chaotic systems to obtain more precise insights about the attractor structure of a canonical turbulent combustion system. Using the tangent solution space directions given by the so-called covariant Lyapunov vectors, an exploration technique of the solution attractor is proposed and tested.

Malik Hassanaly
Department of Aerospace Engineering
University of Michigan
malik.hassanaly@gmail.com

Venkat Raman
University of Michigan
ramanvr@umich.edu

PP1

The Parametrization Method for Center Manifolds

In this poster we will present a version of the Parametrization Method of De la Llave et al. for center manifolds that originate from an equilibrium of an ordinary differential equation. This allows us to describe the dynamical behaviour of the ordinary differential equation near the equilibrium, and to prove (e.g. with the help of validated numerics) whether the equilibrium undergoes a bifurcation. The method will be implemented numerically, and we aim to derive explicit error bounds, so as to optimize the neighbourhood on which the center manifold can be proven to exist. This is joint work with Jan Bouwe van den Berg and Bob Rink.

Wouter A. Hetebrij
Vrije Universiteit Amsterdam
w.a.hetebrij@vu.nl

PP1

Time Series Analysis of Tropically Linear Systems

Tropical mathematics is the study of semirings with min or max as their 'addition' operation. For example the max-plus semiring $\mathbb{R}_{\max} = [\mathbb{R} \cup \{-\infty\}, \oplus, \otimes]$, where

$$a \oplus b = \max\{a, b\}, \quad a \otimes b = a + b, \quad \text{for all } a, b \in \mathbb{R}_{\max}.$$

Interestingly there are certain types of queuing system that admit a max-plus linear dynamical systems description. Note that these systems are linear with respect to the operations max and plus but non-linear with respect to plus and times. Previous research into max-plus linear dynamical systems has focused on the forwards problem of determining a solution from a presupposed model. My poster will report my recent work on the inverse problem of fitting a max-plus linear dynamical model to a time series recording. As an example I will focus on a parallel computing system. The state of the system recorded by the time series includes the times at which different processors complete local tasks. I use tropical algebraic regression techniques to fit a model to this data. This research has possible applications in performance analysis and optimization.

James Hook
University of Bath
University of Bath
james.l.hook@gmail.com

PP1

Graph Automorphisms and Dynamical Patterns in Complex Networks

Past theoretical work has indicated that the automorphisms of the graphs representing complex networks ought to constrain their realized patterns of dynamics. Experimental and simulation work observing the evolution of dynamics on microfabricated square lattices of inhibitory coupled Belousov-Zhabotinsky (BZ) reactions was performed in order to test these theories for highly nonlinear complex networks. The nodes of these experimental networks, unlike commonly theoretically considered Kuramoto coupling, couple repulsively and asymmetrically. These networks exhibit clustering of like-dynamical behavior which vary predictably upon the automorphisms of the network. Beyond illustrating these results, work in controlling these dynamical clusters through external light perturbations to the light-sensitive BZ reaction will be discussed.

Ian M. Hunter
Brandeis Martin A. Fisher School of Physics
Fraden Lab
ianmhunter@brandeis.edu

Seth Fraden, Michael M. Norton
Brandeis University
Department of Physics
fraden@brandeis.edu, mmnorton@brandeis.edu

REMI Boros
Brandeis Martin A. Fisher School of Physics
Fraden Lab
remiboros@brandeis.edu

Thomas Litschel
Brandeis University
Department of Biochemistry
tolitsch@brandeis.edu

PP1

Synchronization and Clustering of Stochastically-Driven Mixed-Mode Oscillators

As complex systems with many interacting components, neural systems exhibit rhythms, reflecting emergent coherence across the activity of the constituent neurons. In the case of the olfactory system in mammals, where the primary neural population features noisy mixed-mode oscillations in the membrane voltage, two prominent rhythms appear. We study the role of the two time scales present in each neuron, corresponding to their large- and small-amplitude oscillations, and of the delayed pulse coupling between the neurons in the rhythmogenesis. We explore the system using both a reduced phase oscillator model, valid for weak noise and weak coupling, and direct numerical simulation. We assess the range of validity of the reduced model and, going beyond it, explore the effects of stronger noise and coupling on the emergent system-level behavior. In particular, we find that the noise exhibits a resonance with the small-amplitude oscillations, causing the variability in the occurrence of the large-amplitude oscillations to change non-monotonically with noise strength. Further, we explore a regime where increasing the noise, while uncorrelated across the oscillators, increases the coherence among them. We elucidate the role of the mixed-mode characteristic of the oscillators and delayed coupling in these phenomena and their effect on the emergent rhythms. Supported by NSF-CMMI 1435358.

Avinash J. Karamchandani
Department of Engineering Sciences and Applied Mathematics
Northwestern University
avijka@u.northwestern.edu

James Graham
Northwestern University
jamesgraham2016@u.northwestern.edu

Hermann Riecke
Applied Mathematics
Northwestern University
h-riecke@northwestern.edu

PP1

Coupling Sample Paths to the Partial Thermodynamic Limit in Stochastic Chemical Reaction Networks

We present a technique for reducing the variance in Monte Carlo estimators of stochastic chemical reaction networks. Our method makes use of the fact that many stochastic reaction networks converge to piecewise deterministic Markov processes in the large system-size limit. The statistics of the piecewise deterministic process can be obtained much more efficiently than those of the exact process. By coupling sample paths of the exact model to the piecewise deterministic process we are able to reduce the variance, and hence the computational complexity of the Monte Carlo estimator.

Ethan Levien
University of Utah
levien@math.utah,edu

Paul C. Bressloff
University of Utah
Department of Mathematics
bressloff@math.utah.edu

PP1

28 Models Later: Best Practices for Modeling the Zombie Apocalypse with Real Data

Zombies! A popular apocalypse scenario in movies, books, and games, but do these portrayals have a biological basis? Would a zombie outbreak really end humanity, or would such an outbreak burn itself out? In movies, zombie outbreaks are caused by a rapidly spreading infection. Diseases tend to be self-limiting but, unlike most diseases, zombie infection does not spread passively. Since the disease is spread by zombies, who themselves are hunting humans, we view the spread of infection as a predator-prey interaction and the question of human extinction becomes a question of how predator and prey interact. To determine the nature of this interaction we ask questions like: Are humans able to protect themselves better in groups? Are all zombies equally effective at hunting? Do zombies compete with each other for human prey or cooperate and share prey? We design models with these mechanisms and fit them to data gathered from "Humans vs. Zombies' (HvZ), a popular role-playing variant of tag common on college campuses. These models compete using information theoretic criteria to determine which models best balance predictivity and simplicity. From this we determine which mechanisms best explain the observed dynamics, giving insight into how a zombie outbreak might play out. Our models indicate that, as might be expected of zombies, they do not cooperate or share resources. Ultimately, results indicate 30% human survival and zombie extinction after a large scale outbreak.

Ian McGahan
Utah State University
ian.mcgahan@aggiemail.usu.edu

PP1

Fractional Order Compartment Models

Compartment models have been used to model a variety of applications including epidemiology, in-vitro disease and pharmacokinetics. Compartment models have been generalised to include fractional derivatives in order to capture a history effect. This generalisation has often been ad-hoc. Regularly leading to a violation of flux-balance and dimension disagreement. This poster addresses these problems and considers the derivation of a fractional order compartment model as a stochastic process, solving the outlined problems and considering some of the applications.

Anna V. Mcgann

UNSW
a.mcgann@unsw.edu.au

Christopher N. Angstmann
UNSW Australia
c.angstmann@unsw.edu.au

Bruce I. Henry
School of Mathematics and Statistics
University of New South Wales
B.Henry@unsw.edu.au

John Murray
School of Mathematics
University of NSW
J.Murray@unsw.edu.au

James Nichols, Austen Erickson
UNSW
j.nichols@unsw.edu.au, a.erickson@unsw.edu.au

PP1

Interjump Statistics of State-Dependent Jump-Diffusion Processes

We propose a formal PDE approach to study the jumps of a jump-diffusion process X_t with state-dependent jump intensity $\lambda(X_t)$. The statistics of the jump component alone are of interest in many applications but are not always feasible to extract through Monte Carlo or full PDE simulations. We formulate an iterative map on the sequence of densities of jump locations, resulting in a governing equation that can be studied directly. From this density, other statistics, including those of the interjump times can be computed. This resulting relationship also illustrates a natural and useful connection between the jump statistics and the stationary density of the full process. Applications of this framework include studying the thresholding of integrate-and-fire and processivity of molecular motors.

Christopher E. Miles
University of Utah
Department of Mathematics
miles@math.utah.edu

James P. Keener
University of Utah
keener@math.utah.edu

PP1

Amplitude and Frequency for a Nonlinear Oscillator by Homotopy Analysis Method

The Homotopy Analysis Method (HAM) has been shown to approximate solutions to nonlinear problems of various types. The method is useful because of the flexibility in defining the auxiliary parameter h and that no assumption concerning relative size of parameters is required. We use HAM to approximate frequency and amplitude of a conservative nonlinear oscillator which has many applications including lasers, epidemics, and microparasites. The oscillator is given by the second-order ordinary differential equation $u' + u + uu' = 0$. We compare our results to those gained from traditional perturbation techniques and briefly discuss conditions for convergence.

Jonathan Mitchell
Hardin-Simmons University
Department of Mathematics
mitchelljonat@sfasu.edu

PP1

Spatially Localized Comb-like Turing Patterns Embedded in Hopf Oscillations

A distinct mechanism for the emergence of spatially localized states embedded in an oscillatory background is presented in the context of 2:1 frequency locking. The localization is of Turing type and appears in two space dimensions as comb-like states in either π phase shifted Hopf oscillations or inside a spiral core. Specifically, the localized states appear outside the 2:1 resonance region and in absence of the well known flip-flop dynamics (associated with collapsed homoclinic snaking) that is known to arise in the vicinity of Hopf-Turing bifurcation in one space dimension. Derivation and analysis of three Hopf-Turing amplitude equations in two space dimensions reveals a distinct pinning mechanism for Hopf fronts which in turn allows the emergence of perpendicular (to the Hopf front) Turing states. The results are shown to agree well with the comb-like core size that forms inside spiral waves. Implications to chlorite-iodide-malonic-acid and periodically driven Belousov-Zhabotinsky chemical reactions, and shaken granular media are also addressed.

Paulino Monroy
Instituto de Ciencias Físicas, Universidad Nacional Autónoma
espaulino@gmail.com

Arik Yochelis
Jacob Blaustein Institutes for Desert Research,
Ben-Gurion University
yochelis@bgu.ac.il

PP1

Information Processing Based on Mutually Delay-Coupled Optoelectronic Oscillators

A novel information processing method based on delayed dynamical systems has been proposed in [Appeltant et al. Nat. Commun. 2011], which is called reservoir computing (RC). RC is based on information processing in the human brain and applicable to tasks which it is hard to computationally solve, such as speech recognition and time-series prediction. In this method, an input information is injected into a delayed dynamical system, which is called "reservoir," the reservoir nonlinearly transforms the signal into a high-dimensional state space in which the signal is represented. The nonlinear transform enables to linearly separate signals in the high-dimensional state space. If the reservoir can transform input signals into higher dimensional state space, it is expected that the performance of RC is improved. In this study, we propose RC based on mutually delay-coupled optoelectronic oscillators, where the reservoir is the mutually delay-coupled optoelectronic oscillators. The mutually coupled oscillators have multiple delay in delayed feedback and coupling. It is expected that the mutually coupled oscillators with different delay times in feedback and coupling can provide complex nonlinear mapping, which can improve the performance of RC. We applied a chaotic time-series prediction task to RC based on mutually coupled oscillators. It is found that our RC system can produce higher prediction accuracy than RC

based on a single optoelectronic oscillator in the task.

Keisuke Nagatoshi, Kazutaka Kanno, Masatoshi Bunsen
Department of Electronics Engineering and Computer Science
Fukuoka University
tl131274@cis.fukuoka-u.ac.jp, kkanno@fukuoka-u.ac.jp,
bunsen@fukuoka-u.ac.jp

PP1

An Investigation of a Structured Fisher's Equation with Applications in Biochemistry

Abstract Recent biological research has sought to understand how biochemical signaling pathways, such as the mitogen-activated protein kinase (MAPK) signaling pathway, influence the migration of a population of cells during wound healing. Fisher's Equation has been used extensively to model experimental wound healing assays due to its simple nature and known traveling wave solutions. This partial differential equation with independent variables of time and space cannot account for the effects of the MAPK signaling cascade on wound healing, however. To this end, we couple a traveling wave analysis with concepts from structured population models to derive a structured Fisher Equation with independent variables of time, space, and biochemical pathway activity and prove the existence of a self-similar traveling wave solution. We also derive a nonautonomous version of the structured Fisher's Equation in time and space to investigate how different patterns of biochemical activity can influence cell migration in a more complicated model.

John Nardini
Department of Mathematics
University of Colorado Boulder
john.nardini@colorado.edu

D. M. Bortz
Department of Applied Mathematics
University of Colorado, Boulder
dmbortz@colorado.edu

PP1

Investigation of Disease Invasion Using a Stochastic SIRκ Model

Disease invasion is the seemingly spontaneous introduction of a disease into a population from an external source. The study of disease invasion is salient to understanding zoonotic spillover events, and can give insight into disease spread throughout human networks. The random nature of disease invasion requires an investigation that includes the use of stochastic disease models. Here we consider both a stochastic and deterministic variation of the Susceptible-Infectious-Recovered (SIR) model that explicitly accounts for infection from an external source; for the sake of distinction we call the new model SIRκ. The SIRκ model can be seen as a relatively simple analog to the more complex SEIDHR Ebola model and will be used to analytically investigate behavior that was observed numerically in the full Ebola model. Of particular interest is the outbreak vulnerability which describes the susceptibility of a population to disease invasion.

Garrett Nieddu
Montclair State University
nieddug1@mail.montclair.edu

Lora Billings, Eric Forgoston
Montclair State University
Department of Mathematical Sciences
billingsl@mail.montclair.edu,
eric.forgoston@montclair.edu

PP1

Finite-Time Attractors and Clustering of Inertial Particles in Fluid Flows

Dynamical systems arising from real-life problems often pose the challenge that they are temporally aperiodic, and that observations are only available over finite time intervals. In such settings, classical concepts from dynamical systems theory typically become ill-defined and standard numerical methods do not apply.
Here, we extend the classical notion of an attractor to finite-time flows with arbitrary time dependence (finite-time attractors). We provide algorithms for numerically constructing finite-time attractors in two and three dimensions. As an application of our approach, we investigate the dynamics of finite size or inertial particles in various two- and three-dimensional fluid flows.

David Oettinger
ETH Zurich
davidoe@ethz.ch

George Haller
ETH, Zurich, Switzerland
georgehaller@ethz.ch

PP1

Chaos and Global Bifurcations in the Rock-Scissors-Paper Bimatrix Game

We consider a Rock-Scissors-Paper game assuming the perfect memory of playing agents X, Y. The interaction matrices depend on two parameters $\epsilon_X, \epsilon_Y \in (-1, 1)$ and the dynamics are described by the coupled replicator equations. We provide the description of naturally appearing heteroclinic network and investigate asymptotic and chaotic behavior in its neighbourhood. It turns out that certain types of behaviours are never possible or appear in the system only for some parameter values, e.g. finite switching. In particular the infinite switching happening near the network cannot be described by the full-shift on two symbols and its form strongly depends on the parameter values. In the system we observe different bifurcation scenarios: e.g. transition from order to chaos (through Hamiltonian case where invariant tori and chaos might be observed), loss of one dimension of the local stable manifold of the subcycle or disappearance/appearance of the local stable/unstable manifolds of the different subcycles at the same time. As well we investigate numerically the existence of the heteroclinic connection between different heteroclinic subcycles (i.e. a superheteroclinic orbit) and its bifurcation to the different heteroclinic connections (forward and backward) from the hyperbolic fixed point (i.e. Nash equilibrium) to the subcycles. [C.Olszowiec "Complex behavior in cyclic competition bimatrix games", https://arxiv.org/pdf/1605.00431v4.pdf]

Cezary Olszowiec
Imperial College London

cmo14@ic.ac.uk

PP1

Adaptive Neuronal Networks in Olfaction: Mechanism of Network Evolution and Information Processing

While learning in the nervous system is usually associated with changes in synaptic weights, in the olfactory system it is characterized by structural plasticity, i.e., the persistent addition and removal of neurons (neurogenesis) and the extensive formation and removal of spines that provide connections between neurons. We present a computational model to investigate the network connectivities emerging from both of these structural plasticity mechanisms and the associated processing of inputs by these networks. We find that Hebbian spine stability both explains the experimentally observed enhancement of spine stability with spine age and leads to pattern separation. A key element of the network evolution and the resulting information processing is the presence of both bottom-up input from the sensory neurons and top-down input from the cortex. The neuronal turnover via adult neurogenesis renders a network structure that allows cortical inhibition of a very specific set of neurons, which endows the network with the ability to suppress familiar, distracting stimuli.

Jaesuk Park, Hongyu Meng
Applied Mathematics
Northwestern University
jaesukpark2017@u.northwestern.edu,
hongyumeng2013@u.northwestern.edu

Martin Wiechert
Department of Physiology
U. Bern, Switzerland
martin.wiechert@gmx.de

Hermann Riecke
Applied Mathematics
Northwestern University
h-riecke@northwestern.edu

PP1

Activity Patterns of Neuronal Network with Voltage-Sensitive Piecewise Smooth Coupling

We present an analysis of activity patterns in a neuronal network of three mutually inhibitory cells with voltage-sensitive piecewise smooth coupling. While standard fast-slow analysis fails to describe the dynamics during fast jumps due to the voltage-sensitive nature of coupling, piecewise smoothness of coupling enables us to consider a sequence of fast subsystems in piecewise way. Our analysis shows that slow dynamics as well as fast dynamics incorporate to determine where fast jumps actually go.

Choongseok Park
Department of Mathematics
North Carolina A&T State University
cpark@ncat.edu

Jonathan E. Rubin
University of Pittsburgh
Department of Mathematics
jonrubin@pitt.edu

PP1

Quantifying the Role of Folding in Nonautonomous Flows: the Unsteady Double Gyre

The combination of stretching and folding will be a reason to establish the chaos in the chaotic dynamics. As a result of this, it is required to analyze the stretching and folding to quantify the chaos. Although there are many techniques which can be used to analyze stretching, there are only few studies which are useful to quantify folding. In this poster presentation, we will show how the folding can be characterized in terms of curvature along stable manifold and unstable manifold. Also we will provide more detailed analytical computation and numerical study of the canonical example of the nonautonomous double gyre. While the Smale-Birkhoff Theorem is well-known to imply chaos for either transversal homoclinic intersections or heteroclinic intersections associated with a heteroclinic network, we show why folding-driven chaos is also implied in the double gyre, in which the heteroclinic intersection is not part of a transversally intersecting heteroclinic network. Our method of using curvature to identify folding applies to general nonautonomous flows in two dimensions, defined for either finite or infinite times.

Kanaththa G. Priyankara
SIAM
priyankg@clarkson.edu

Erik Bollt
Clarkson University
bolltem@clarkson.edu

Sanjeeva Balasuriya
University of Adelaide
sanjeevabalasuriya@yahoo.com

PP1

Prediction of Dynamical Systems by Symbolic Regression

We study the modeling and prediction of dynamical systems based on conventional models derived from measurements. Such algorithms are highly desirable in situations where the underlying dynamics are hard to model from physical principles or simplified models need to be found.We focus on symbolic regression methods as a part of machine learning. These algorithms are capable of learning an analytically tractable model from data, a highly valuable property. Symbolic regression methods can be considered as generalized regression methods. We investigate two particular algorithms, the so-called fast function extraction which is a generalized linear regression algorithm, and genetic programming which is a very general method. Both are able to combine functions in a certain way such that a good model for the prediction of the temporal evolution of a dynamical system can be identified. We illustrate the algorithms by finding a prediction for the evolution of a harmonic oscillator based on measurements, by detecting an arriving front in an excitable system, and as a real-world application, the prediction of solar power production based on energy production observations at a given site together with the weather forecast.

Markus Quade
University of Potsdam
Ambrosys GmbH

markus.quade@uni-potsdam.de

Markus W Abel
Universität Potsdam
markus.abel@physik.uni-potsdam.de

Kamran Shafi
UNSW, ADFA, Canberra BC ACT 2610, AUSTRALIA
k.shafi@adfa.edu.au

Robert K. Niven
he University of New South Wales, Canberra, Australia.
r.niven@adfa.edu.au

Bernd Noack
LIMSI-CNRS
Technical University Braunschweig
bernd.noack@limsi.fr

PP1

Ensemble-Based Topological Entropy Computation

We introduce the Ensemble-Based Topological Entropy Computation (E-Tec) algorithm. It computes how an initial codimension-one simplex evolves under an ensemble of trajectories. In order to generalize this topological data analysis to higher dimensions, we evolve an initial codimension-zero triangulation, with vertices of the simplex and triangulation attached to trajectories from the ensemble. When other trajectories intersect the simplex, rather than penetrate it, the simplex is stretched like a piece of elastic. In this manner, the simplex will be stretched and folded producing an exponential proliferation of codimension-one simplices. The exponential growth rate is the topological entropy, a quantitative measure of the complexity and diversity of orbits in a dynamical system.

Eric Roberts
University of California, Merced
eroberts5@ucmerced.edu

Kevin A. Mitchell
University of California, Merced
Physics
kmitchell@ucmerced.edu

Suzanne Sindi
University of California, Merced
ssindi@ucmerced.edu

PP1

Optimal Regularization for Prediction in Nonlinear Dynamical Inverse Problems

In dynamical inverse problems, the goal is to infer the values of a model systems state variables and parameters from an observed system, and then use this model system to make predictions of future observations. Data assimilation solves this problem by transferring information from the observed system to the model. Due to measurement and model errors, the data assimilation is statistical. One should thus seek expected values of functions on the models states and parameters using a probability distribution conditioned on the observed data, and with a prior distribution containing the dynamical model constraints as a regularization term. It is a well-known result in linear inverse problems that the strength of this regularization term has an optimal value for producing robust estimates and predictions, using for example the L-curve criterion with Tikhonov regularization. We extend this result to nonlinear dynamical inverse problems, and using a variational approximation to a path-integral formulation of data assimilation, show that the regularization strength has an optimality condition for prediction quality and robustness of state and parameter estimates. This result has important implications for variational methods such as 4DVar, in which case overenforcing the model constraints may severely limit ones ability to produce high-quality predictions of an observed system.

Paul Rozdeba
University of California, San Diego
prozdeba@physics.ucsd.edu

PP1

Center Manifolds Via Lyapunov-Perron

The Lyapunov-Perron operator is a theoretical method used to show the existence of the invariant manifold. In 2005, M.S. Jolly and R. Rosa presented an algorithm for solving systems with center manifolds based on discretizing the Lyapunov-Perron (L-P) operator. However, this discretization can be difficult and expensive to implement. First, we provide detailed proofs of the construction of the center manifold by the L-P operator under the Jolly-Rosa framework. Second, we present an algorithm based on a boundary value formulation of the operator. Importantly, the algorithm is simple and can be adopted by any generic scheme, such as the Runge-Kutta methods. We implement the algorithm, test it with several examples, and discuss applications.

Emily Schaal, Yu-Min Chung
College of William and Mary
eeschaal@email.wm.edu, ychung@wm.edu

PP1

Using the Atomic Force Microscope to Measure Stiffness at the Nano-Scale

Originally confined to mapping topography, new methods have advanced the operating potential of an atomic force microscope (AFM) to include measurements of the stiffness, magnetism and thermal conductivity of a sample. The ability to measure stiffness is of particular importance to the nuclear power industry, specifically for models predicting the life of steel components, as few techniques work at the micro and nanometre scale that do not cause substantial damage to the sample; potentially destroying it or causing unknown effects on results. One method for measuring stiffness at the nanoscale, contact resonance AFM, uses the nonlinear properties of an AFM probe and considers its shift in resonant frequency as it comes into contact with the sample. This shift is a result of the nonlinear tip-sample interaction, influenced by the geometry, material properties, and the surrounding fluid. It yields stiffness variation for both hard and soft samples with up to nanometre resolution, but has so far been limited to achieving relative measurements. In this talk, we describe new modelling results that show how to obtain absolute stiffness values. We achieve this by developing a dynamical system model of the micro-mechanical cantilever, combined with the fluid dynamics of the surrounding medium, and new cantilever calibration methods. We demonstrate the improved technique in action, via experiments on a range of

materials.

Namid Shatil
University of Bristol
Nam.Shatil@bristol.ac.uk

Martin Homer
University of Bristol
Department of Engineering Mathematics
martin.homer@bristol.ac.uk

Loren Picco
Interface Analysis Centre,
University of Bristol
loren.picco@bristol.ac.uk

Oliver Payton
Department of Engineering Mathematics,
University of Bristol
oliver.payton@bristol.ac.uk

PP1

Cone-Dynamical Discriminants: Decoding Neural Velocity

In neural computation, researchers frequently study complex brain networks in order to understand how these systems represent information. These approaches, which increasingly involve machine learning have proved fruitful for gross brain states such as attention or sleep, but with rather poor accuracy for higher cognitive processes. One reason for such limitation may be that the current approaches based upon mean amplitude or frequency are poorly suited to studying information encoded in chaotic dynamics implicated in higher cognition. For these applications, we propose a new method by which to decode information from high dimensional, potentially chaotic dynamics motivated by recent extensions of monotone dynamic theory. In brief, these theoretical advances show how the behavior of a system may be constrained by the invariance of its derivatives in certain generalized cones. We apply conic invariance to differentiate dynamic processes by decoding the underlying vector field of an observed time series. These classifications are performed in real time to individual data points thus enabling second-to-second discrimination of the system dynamics and, potentially, latent state. We provide an analytic solution to differentiate states using balancing properties of derivatives. We present results demonstrating the power of the approach over current methods in diverse settings including brain-computer interfaces, clinical diagnosis/monitoring, and decoding human cognition.

Matthew Singh
Washington University in St. Louis
f.singh@wustl.edu

ShiNung Ching
Washington University in St. Louis
Dept. of Electrical and Systems Engineering
shinung@wustl.edu

PP1

Effects of Time-Delay in a Model of Motor Coordination

Motor coordination is an important feature of intra- and inter-personal interactions, and several scenarios from finger tapping to human-computer interfaces have been investigated experimentally. In the 1980s, Haken, Kelso and Bunz formulated a coupled nonlinear two-oscillator model, which has been shown to describe many observed aspects of coordination tasks. We present here a bifurcation study of this model, where we consider a delay in the coupling. The delay is associated with delays in processing sensory information and human reaction times. We use numerical continuation to show that delay has a significant effect on the observed dynamics. In particular, we find a much larger degree of bistablility between in-phase and anti-phase oscillations in the presence of a frequency detuning.

Piotr Slowinski
University of Exeter, UK
p.m.slowinski@exeter.ac.uk

Krasimira Tsaneva-Atanasova
University of Exeter
k.tsaneva-atanasova@exeter.ac.uk

Bernd Krauskopf
University of Auckland
Department of Mathematics
b.krauskopf@auckland.ac.nz

PP1

Predicting Financial Stock Crashes Using Ghost Singularities

The analysis of a financial dynamical model which exhibits bubbles and crashes is presented. In addition to bifurcation analysis of equilibria and periodic orbits, scaling laws governing the period and amplitude of bubbles are provided analytically. Moreover, a notion of 'ghosts of finite-time singularities' is introduced. This concept will be used to predict time of a crash by estimating the periodicity of bubbles with periodicity of solutions for truncated normal form close to a bifurcation point. Finally, the idea is tested on the theoretical stochastic system as well as on real financial data.

Damian T. Smug, Peter Ashwin
University of Exeter, UK
d.smug@exeter.ac.uk, p.ashwin@exeter.ac.uk

Didier Sornette
Department of Management, Technology and Economics
ETH Zurich
dsornette@ethz.ch

PP1

Stability of Entrainment in Coupled Oscillators

Complex systems are ubiquitous and often difficult to control, hence models for the control of such systems are of growing interest. As an example, we examine the design of the entrainment process for a system of coupled phase oscillators that are all subject to the same periodic driving signal. It was recently shown that in the absence of coupling, an appropriately designed input can result in each oscillator attaining the frequency of the driving signal, with a phase offset determined by the oscillator's natural frequency. We consider a special case in which the coupling tends to destabilize the phase configuration to which the driving signal would send the oscillators in the absence of coupling. In this setting we use a mean-field approach to derive stability results that capture the trade-off between

driving and coupling, and compare these results to the unforced version (i.e. the standard Kuramoto model).

Jordan Snyder
University of California, Davis
jasnyder@math.ucdavis.edu

Anatoly Zlotnik, Aric Hagberg
Los Alamos National Laboratory
azlotnik@lanl.gov, hagberg@lanl.gov

PP1

Time-Variant Estimation of Connectivity

Interactions of network structures are of particular interest in many fields of research since they promise to disclose the underlying mechanisms. Additional information on the direction of interactions is important to identify causes and their effects as well as loops in a network. This knowledge may then be used to determine the best target for interference, for example, stimulation of a certain brain region, with the network. Renormalized partial directed coherence has been introduced as a means to reconstruct the network structure by investigating Granger causality in multivariate systems. A major challenge in estimating respective coherences is a reliable parameter estimation of vector autoregressive processes. We discuss two shortcomings typical in relevant applications, i.e. non-stationarity of the processes generating the time series and contamination with observational noise. To overcome both, we present an approach combining renormalized partial directed coherence with state space modelling. We present the application of this approach to different neural signals.

Linda Sommerlade
Institute for Complex Systems and Mathematical Biology
University of Aberdeen
l.sommerlade@abdn.ac.uk

Claude Wischik
TauRx Therapeutics Ltd
cmw@taurx.com

Bjoern Schelter
Institute for Complex Systems and Mathematical Biology
b.schelter@abdn.ac.uk

PP1

Dynamical Characterizations of Complex Behavior in Consensus Networks with Stochastic Link Failures

Consensus dynamics of multi-agent systems on networks has long been studied in both engineering and social-science contexts with both stochastic and deterministic models. Recently, it has been discovered that Lévy-like hyper-jump diffusion emerges in consensus networks when stochastic link failures are incorporated into their network models; that is, the size of these jumps is power-law distributed, as in Lévy flight behavior. In the engineering literature where this phenomenon has been studied, the focus has been on developing update rules that ensure convergence in scenarios with stochastic link failures. However, given that Lévy flights emerge in natural systems as efficient search strategies, it could also be potentially useful to induce them in stochastic search algorithms to improve upon metaheuristics like simulated annealing. Furthermore, detailed characterization of these behaviors may help to better understand sudden shifts in public opinion. Here, we study the effect of different parameters in stochastic consensus networks on the emergence of Lévy flights, and we make use of Local Active Information Storage, a framework based on transfer entropy, to develop tools for predicting the onset of a jump based on past data from the temporal process. Such tools may be specifically applicable to predict similar opinion jumps in social systems and generally useful for developing new, multi-scale models for the dynamics of information across networks.

Xin Su
Arizona State University
xin.victor.su@gmail.com

Theodore Pavlic
Arizona State University
School of Computing/Informatics/Decision Systems Engineering
tpavlic@asu.edu

PP1

Information Theoretical Noninvasive Damage Detection in Bridge Structures

Damage detection of mechanical structures such as bridges is an important research problem in civil engineering. Using spatially distributed sensor time series data collected from a recent experiment on a local bridge in upstate New York, we study noninvasive damage detection using information-theoretical methods. Several findings are in order. First, the time series data, which represent accelerations measured at the sensors, more closely follow Laplace distribution than normal distribution, allowing us to develop parametric estimates for various information-theoretic measures such as entropy and mutual information. Secondly, as damage is experimentally introduced by the removal of bolts of the first diaphragm connection, the interaction between spatially nearby sensors as measured by mutual information become weaker, suggesting that the bridge has been "loosened". Finally, using a proposed oMII procedure to prune away indirect interactions, we found that the primary direction of interaction or influence aligns with the traffic direction on the bridge even after damaging the bridge.

Amila N. Sudu Ambegedara
Clarkson University
suduaman@clarkson.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

Kerop Janoyan, Erik Bollt
Clarkson University
kjanoyan@clarkson.edu, bolltem@clarkson.edu

PP1

3D Super-Lattice Solutions in Reaction-Diffusion Systems

Earlier research on reaction-diffusion systems has focused on two-dimensional domains and found a wealth of solutions defined on simple and super-lattices. Even in three dimensions the solutions on the simple, face centered and body centered cubic lattices have been studied. We explore three-dimensional solutions on the super-lattices corresponding to 24- and 48-dimensional representations of

the octahedral group.

Timothy K. Callahan, Rebecca Tobin
Embry-Riddle Aeronautical University
Department of Physics
callahat@erau.edu, tobinr@my.erau.edu

PP1

Topological Complexity of the Greenberg-Hastings Cellular Automata

The modeling and analysis of excitable media is predominantly done by PDEs, in particular of FitzHugh-Nagumo-type. A phenomenological alternative are models with discrete time, space and states, i.e. cellular automata (CA). A special one-dimensional CA for excitable media was introduced by Greenberg and Hastings in the late 1970's. We revisit a topological complexity result for the three-state model (rest state, refractory state, excited state) by R. Durrett and J. Steif in the 90's, and give an explicit description of the non-wandering set. Next, we generalize this result by changing the alphabet by an arbitrary number of refractory states. It turns out that the model's complexity results from the annihilation events of pulses upon collision at certain space-time locations. Moreover, we give an estimation of the topological entropy in case of more than one excited state. Finally, we formulate some open questions and outline connections to the PDE perspective.

Dennis Ulbrich, Jens Rademacher, Marc Keeböhmer
University of Bremen
dennisu@math.uni-bremen.de, jdmr@uni-bremen.de, mhk@math.uni-bremen.de

PP1

A Mathematical Model for Post-Replicative DNA Methylation Dynamics

DNA methylation is an important epigenetic mechanism used by cells to repress gene expression. Interestingly, DNA replication, a function necessary for cell division, disrupts the methylation pattern. Since perturbed methylation patterns are associated with aberrant gene expression and cancer, DNA methyltransferases (Dnmts) must restore the correct pattern following DNA replication. However, the exact mechanisms of this restoration remain under investigation. We propose a mean-field model to study the dynamics of post-replicative restoration of methylation patterns. Dnmts perform methylation by adding a methyl group to cytosines at CpG sites, in which cytosine and guanine are consecutive in the DNA. These CpG sites are found in regions of high density, termed CpG islands (CGIs), and regions of low density in the genome. Nearly every CpG site in a CGI has the same state, either methylated or unmethylated. Meanwhile, nearly all CpG sites in regions of low density are methylated. We developed a stochastic model of the restoration of the methylation pattern following replication by considering the methylation activity of Dnmts. Our model predicts that the methylation of CpG sites exhibits bistable behavior, with methylation in CGIs maintained primarily by the processivity of Dnmts, while the methylation of CpG sites outside of CGIs is maintained by localization of Dnmts to the replication fork.

Kiersten Utsey
University of Utah
Department of Mathematics
utsey@math.utah.edu

James P. Keener
University of Utah
keener@math.utah.edu

PP1

Study of Some Nonlocal Transport Equations: Application to Stochastic Neural Dynamics

This work deals with the analysis of the limit equation (mean field) of a stochastic model of spiking neurons interacting with spikes and described as a piecewise deterministic Markov process. The limit equation, recently derived by N.Fournier etal., describes the distribution of the membrane potential as a nonlinear and non-local transport equation with boundary condition. We first focus on the case where there is no electrical synapses stochastic model reduces to a pure jump process. In this case, the mean field admits a $1D$ parametrised family of stationary solutions. The linearised equation around a stationary solution involves a positive C^0-semigroup which enables to precisely pinpoint the spectrum of the infinitesimal generator. The main difficulty is that the nonlinear semigroup is non differentiable. We overcome this issue with a time rescaling and a cut-off. We then show the exponential stability of the stationary solutions. This very interesting result can be recast as the existence of an attracting center manifold for a transport equation. Due to their non regularising properties, the existence of such manifold is notoriously difficult. In the case with electrical synapses, numerical simulations show the occurence of a Hopf bifurcation. In particular, this (numerically) breaks a recent conjecture about the stability of the stationary distribution.

Romain Veltz
INRIA Sophia-Antipolis
romain.veltz@inria.fr

PP1

Resource-Transport Dynamics Induces Criticality in Networks of Excitable Nodes

Brain function needs to be constantly regulated to avoid too much or too little activity. More precisely, it has been hypothesized that synapse strengths are tuned so that the brain operates at the critical point of a phase transition, characterized by experimentally observed power-law distributed patterns of activity known as neuronal avalanches. A fundamental question is what mechanisms regulate the synapse strengths so that the network operates at this critical point. We propose a model where synapse strengths are regulated by metabolic resources distributed by a secondary network of glial cells. We find that this multilayer network robustly produces power-law distributed avalanches over a wide range of parameters, and that the glial cell network protects the system against the destabilizing effect of local variations in parameters. For homogeneous networks, we derive a reduced 3-dimensional map which reproduces the behavior of the full system and gives insights into the robustness of the critical state to parameter changes.

Yogesh Virkar
Department of Computer Science
University of Colorado, Boulder
yogesh.virkar@colorado.edu

Woodrow Shew
University of Arkansas
woodrowshew@gmail.com

Juan G. Restrepo
Department of Applied Mathematics
University of Colorado at Boulder
Juanga@Colorado.EDU

Edward Ott
University of Maryland
Inst. for Research in Electronics and Applied Physics
edott@umd.edu

PP1

Hamiltonian Structure and Stability Results for Idealised Flows on a Three Dimensional Periodic Domain

The Euler Equations for inviscid incompressible flows provide a simplified model for studying fluid dynamics. We consider an anisotropic three dimensional periodic domain. We first show that this problem has a new Poisson structure in Fourier space for the vorticity formulation , opening the possibility of Energy-Casimir type stability results. These equations also admit a family of shear flows with vorticity $\Omega^*(\mathbf{x}) = \cos(\kappa_1 p_1 x_1 + \kappa_2 p_2 x_2 + \kappa_3 p_3 x_3)$ for p_i integers. We first show that the linearised system around these stationary solutions almost always reduces to the equivalent linearised system in the two-dimensional problem. This demonstrates there are linearly stable solutions of the form $\cos(\kappa_1 p_1 x_1)$ for sufficiently large values of κ_2, κ_3. This is an extension to the shear flow stability result due to Arnold. We then show that for most other values of p_i and κ_i, there is linear instability. These results are an extension of results from [Dullin & Marangell & Worthington, *Instability of Equilibria for the 2D Euler Equations on the torus*, SIAM Journal on Applied Mathematics, 76(4), (2016) 1446-1470] and [Dullin & Worthington, *Stability Results for Idealised Shear Flows on a Rectangular Periodic Domain*, arXiv:1608.06109 [math.DS], 2016].

Joachim Worthington
University of Sydney, Australia
joachimworthington@gmail.com

PP1

Bifurcations in the Piecewise-Linear Standard Nontwist Map

A piecewise-linear version of the area-preserving standard nontwist map [D.del Castillo, J.M. Greene and P.J. Morrison, Physica D **91**, 1 (1996)] is considered. Using symmetry lines and involution maps I compute periodic orbits to analyze various bifurcations, including periodic orbit collisions and separatrix reconnections, that can suppress or enable global transport.

Alexander Wurm
Department of Physical & Biological Sciences
Western New England University
awurm@wne.edu

PP1

Weak-Noise-Induced Transitions with Inhibition and Modulation of Neural Spiking Dynamics

We analyze the effect of weak-noise-induced transitions on the dynamics of a neuron model in a bistable state consisting of a stable fixed point and a stable unforced limit cycle. Bifurcation and slow-fast analysis give conditions on the parameter space for the establishment of this bistability. In the parametric zone of bistability, weak-noise amplitudes may strongly inhibit the neurons spiking activity. Surprisingly, increasing the noise strength leads to a minimum in the spiking activity, after which the activity starts to increase monotonically with increase in noise strength. We investigate this phenomenon in details and show that it always occurs when the initial conditions lie in the basin of attraction of the stable limit cycle. For initial conditions in the basin of attraction of the stable fixed point, the phenomenon however disappears, unless the time-scale separation parameter of the model is bounded within some interval. Using the tools from stochastic sensitivity analysis of attractors, we provide a theoretical explanation to this phenomenon.

Emar Marius Yamakou, Juergen Jost
Max Planck Institute for Mathematics in the Sciences
yamakou@mis.mpg.de, jost@mis.mpg.de

PP1

Demographic Noise Slows Down Cycles of Dominance in Ecological Models

We study the phenomenon of cyclic dominance in the paradigmatic Rock–Paper–Scissors model, as occuring in both stochastic individual-based models of finite populations and in the deterministic replicator equations. The mean-field replicator equations are valid in the limit of large populations and, in the presence of mutation and unbalanced payoffs, they exhibit an attracting limit cycle. The period of this cycle depends on the rate of mutation; specifically, the period grows logarithmically as the mutation rate tends to zero. However, this behaviour is not reproduced in stochastic simulations with a fixed finite population size. Instead, demographic noise present in the individual-based model dramatically slows down the progress of the limit cycle, with the typical period growing as the reciprocal of the mutation rate. Here we develop a theory that explains these scaling regimes and delineates them in terms of population size and mutation rate. We identify a further intermediate regime in which we construct a stochastic differential equation model describing the transition between stochastically-dominated and mean-field behaviour.

Qian Yang
University of Bath
qy300@bath.ac.uk

PP1

A Stable Numerical Algorithm for Calculating the Rate of Exponential Forgetting in HMM

We consider a finite state hidden Markov model (HMM) with multidimensional observations. Under some mild assumptions, the prediction filter forget almost surely the initial condition exponentially fast. However, it is very difficult to calculate this asymptotic rate of exponential loss of memory analytically. We restate this problem in the setting of random dynamical system and use the Lyapunov exponents of the induced random dynamical system defined in the projective space $\mathbb{R}^{n-1}$ to approximate the convergence rate. Finally, we propose a stable numerical algorithm to calculate the rate of exponential forgetting semi-analytically. The numerical simulation result and comparison with current upper bound in literature will be shown in the presentation.

Xiaofeng Ye, Yian Ma

University of Washington
yexf308@uw.edu, yianma@u.washington.edu

Hong Qian
Department of Applied Mathematics
University of Washington
hqian@u.washington.edu

PP1

Interactions of Solitary Pulses of *E. Coli* in a One-Dimensional Nutrient Gradient

We study an anomalous behavior observed in interacting *E. coli* populations. When two populations of *E. coli* are placed on opposite ends of a long channel with a supply of nutrient between them, they will travel as pulses toward one another up the nutrient gradient. We present experimental evidence that, counterintuitively, the two pulses will in some cases change direction and begin moving away from each other and the nutrient back toward the end of the channel from which they originated. Simulations of the Keller-Segel chemotaxis model reproduce the experimental results. To gain better insight to the phenomenon, we introduce a heuristic approximation to the spatial profile of each population in the Keller-Segel model to derive a system of ordinary differential equations approximating the temporal dynamics of its center of mass and width. This approximate model simplifies analysis of the global dynamics of the bacterial system and allows us to efficiently explore the qualitative behavior changes across variations of parameters, and thereby provides experimentally testable hypotheses about the mechanisms behind the turnaround behavior.

Glenn S. Young
Pennsylvania State University
Department of Mathematics
gsy4@psu.edu

Mahmut Demir
Department of Molecular, Cellular and Developmental Biology
Yale University
mahmut.demir@yale.edu

Hanna Salman
University of Pittsburgh
Department of Physics and Astronomy
hsalman@pitt.edu

Bard Ermentrout, Jonathan E. Rubin
University of Pittsburgh
Department of Mathematics
bard@pitt.edu, jonrubin@pitt.edu

PP1

Non-Cooperative Games with Cost of Information

In classical game theory, competitive games involving two players typically deal with full information situations, in which each players know all of the rules of the game, as well as all strategy choices and associated payoffs for both players; the only uncertainty is what the opposing player will choose - what strategy will be played. We study two-player games in which one or both players may obtain partial information about the other players choice, but with some cost. We propose a formalism in which partial information can be purchased, and adapt the Nash equilibrium approach to this situation. Distinct transitions are observed which depend on this cost function, and ramifications are discussed.

Andrew Belmonte
Department of Mathematics, Pennsylvania State University
andrew.belmonte@gmail.com

Matthew Young
Department of Mathematics
Pennsylvania State University
mjy5068@psu.edu

PP1

Lateral Inhibition Networks in Rat Olfactory Bulb

The first structure involved in mammalian olfactory processing, the olfactory bulb, is largely comprised of functional units, glomeruli, that receive direct inputs from olfactory receptors. Glomeruli are thought to communicate with each other through a network of inhibitory short axon cells. The extent and specificity of the inter-glomerular inhibitory network is actively debated. However, it is agreed that the odor-evoked patterns of glomeruli activity resulting from the network probably play an important role in odor coding. In this study we make a network model of the inter-glomerular connectivity in the olfactory bulb by using data to constrain the number of inhibitory cells in each glomerulus, the distribution of the number of outgoing connections per cell, and the number and location of targets each cell contacts. We then derive analytically the in-degree distribution of this network and compute its other graph-theoretic properties as we allow the specificity of connections to vary. We find that the network properties can be substantially different from those of the well-studied classes of scale-free, small-world and random networks. Finally, we add firing-rate dynamics to the network. Using realistic receptor activation profiles as inputs to our network, we study the effect of the connection specificity on the resulting patterns of glomerular activity.

Daniel R. Zavitz
University of Utah
Department of Mathematics
danielzavitz1@gmail.com

Alla Borisyuk
University of Utah
Dept of Mathematics
borisyuk@math.utah.edu

Matt Wachowiak, Isaac Youngstrom
University of Utah School of Medicine
Department of Neurobiology & Anatomy
matt.wachowiak@utah.edu,
isaac.youngstrom@neuro.utah.edu

PP2

Social Experience Reconfigures Decision-Making Circuits in Zebrafish

Understanding how social factors influence nervous system function is of great importance. Using zebrafish as a model system, we demonstrate how social experience affects decision-making to enable animals to produce socially appropriate behavior. Based on experimental evidence and computational modeling, we show that behavioral decisions reflect the interplay between competing neural cir-

cuits whose activation thresholds shift in accordance with social status. We demonstrate this through analysis of the behavior and neural circuit responses that drive escape and swim behaviors in fish. Our computational model of the escape and swim circuits replicates our findings and suggests that social status-related shift in circuit dynamics could be mediated by changes in the relative excitability of the escape and swim networks.

Sungwoo Ahn
Arizona State University
ahns15@ecu.edu

Thomas Miller, Katie Clements
East Carolina University
millert15@students.ecu.edu,
clementsk10@stduents.ecu.edu

Choongseok Park
Department of Mathematics
University of Pittsburgh
21cspark@gmail.com

Eoon Hye Ji
UCLA
graceji85@gmail.com

Fadi Issa
East Carolina University
issaf14@ecu.edu

PP2

Network Bursting in Melibe Swim CPG

Central pattern generators(CPGs) are neural networks, which can produce rhythmic activity and are responsible for generating various oscillatory behaviors like swim locomotion. We develop a Hodgkin-Huxley type highly detailed and biologically plausible model using the extensive data intracellularly recorded from swim CPG of the sea slug *Melibe Leonida*. We study the rhythmogenesis of oscillatory patterns emerging in such network circuits consisting of half-center oscillators, which are the building blocks of many neural networks including CPGs. The four interneurons in the modeled CPG are coupled by multiple chemical inhibitory and excitatory synapses, which are represented by alpha and dynamical models.

Deniz Alacam
Georgia State University
Mathematics Department
dalacam1@student.gsu.edu

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

PP2

Theory and Computation of Nonlinear Deformation Spectra of Flows

We present the mathematical theory and efficient computational framework for spectral information of the nonlinear (large) deformation tensor for flows on general Riemannian manifolds characterized by a generic metric tensor. The eigenvalues of the nonlinear deformation tensor have applications in fluid mechanics. A common example of flows on manifolds are flows on a sphere with geophysical applications. For such flows, besides considering the generic Riemannian manifold approach, we present an alternative method by using Euclidean representation of the equations with a projection that yields to a set of coupled differential algebraic equations. In order to validate this numerical solution of differential algebraic equations, we have derived an exact solution for the eigenvalues and eigenvectors of the deformation tensor for vortex flows on the sphere and demonstrate that the numerical results are in agreement with the exact solutions up to the numerical integration tolerance.

Siavash Ameli
University of California, Berkeley
sameli@berkeley.edu

PP2

Symbolic Dynamics Applied to a Numerical Simulation of a Perturbed Hill's Spherical Vortex.

3D homotopic lobe dynamics (HLD) is a new symbolic method of describing topological dynamics for fully 3D systems. Here we apply this new method to a numerically computed perturbed Hill's spherical vortex flow. We consider the scattering of passive tracers that are drawn into and then ejected from the vortex. We focus on the numerical computation of fractal scattering functionsthe time advected particles are trapped within the vortex as a function of two impact parameters. We compare the fractal self-similarity of these scattering functions to those predicted by 3D HLD. Our new method also produces a lower bound on the topological entropy of our system which approaches the true topological entropy as we add more numerical data.

Joshua Arenson
University of California Merced
jarenson@ucmerced.edu

Spencer A. Smith
Mount Holyoke College
smiths@mtholyoke.edu

Kevin A. Mitchell
University of California, Merced
Physics
kmitchell@ucmerced.edu

PP2

Channel Capacity of Cardiac Action Potential Transmission and Spiral Wave Initiation

Alternans of action potential duration (APD) is an oscillatory dynamics of cardiac cells that could lead to conduction block and spiral wave initiation. However, it is unclear as to how this intrinsic property of the cardiac tissue impacts information transmission at the tissue level. To quantify the channel capacity of information transmission in in the presence of APD alternans and conduction block, we performed numerical simulation of cardiac tissue using the Fenton-Karma model that is known to exhibit these properties. We stimulated one cell in a one-dimensional cable and a two-dimensional lattice with a fixed basic cycle length (BCL) that ranged from 200 msec and 300 msec. For each cell, the time series of cardiac action potential was coarse-grained to 1 when excited (during the APD at 90% repolarization, or APD90) or 0 when resting. We considered the cell of stimulus as an information source/transmitter with an input X, any other cell in the system as a receiver/destination with an output Y, and the intervening cells between them as a binary asymmetric channel. By calculating the probability of transmission errors, we obtained the channel capacity as a function of BCL and distance away from the information source. Our approach is clinically applicable to quantify the propensity of the cardiac tissue to develop lethal arrhythmia in human patients.

Ameneh Asgari-Targhi
University of Glasgow
School of Mathematics and Statistics,
a.asgari-targhi.1@research.gla.ac.uk

Hiroshi Ashikaga
Johns Hopkins University School of Medicine
hashika1@jhmi.edu

PP2

Computing the Optimal Path for Stochastic Populations Coupled Through Migration

We consider a two-population stochastic model where both populations are connected through migration. Each population of species undergoes birth and annihilation events. Using a master equation approach and a WKB (Wentzell-Kramers-Brillouin) approximation, we find the theoretical mean time to extinction. Numerical Monte Carlo simulations agree well with the analytical results for a single population, and also allow for an exploration of how changes in migration rates affect the behavior of extinction events in coupled populations. Using an iterative method, we numerically compute the optimal path to extinction and the mean time to extinction for coupled populations. Furthermore, we explore how changes in migration rates in a coupled system affect the curvature of the optimal path.

Alexa Aucoin
Montclair State University
aucoina1@montclair.edu

Lora Billings, Eric Forgoston
Montclair State University
Department of Mathematical Sciences
billingsl@mail.montclair.edu,
eric.forgoston@montclair.edu

PP2

Conservation Laws in Nonlocal Equations

In this poster we consider the dynamics of the shift map on the set of bounded solutions to the *nonlocal* equation

$$Au' + K * u + f(u) = 0,$$

where K is a symmetric convolution kernel. Such equations arise naturally when studying coherent structures in e.g. spatially discretized parabolic equations, neural field equations, or nonlocal NLS. We will show how to construct conserved quantities (or, when $A > 0$, a Lyapunov function) for the shift dynamics. We then discuss some dynamical consequences of these structures. This is joint work with Arnd Scheel (University of Minnesota), Jan Bouwe van den Berg (VU Amsterdam), and Rob Vandervorst (VU Amsterdam).

Berry Bakker
VU University Amsterdam
b.bakker@vu.nl

PP2

Three-Dimensional Chattering of Rigid Bodies

Ideally rigid objects establish sustained contact with one another via an infinite sequence of collisions accumulating in finite time. Similar phenomena in hybrid dynamical systems are often referred to as Zeno behaviour or complete chatter (CC). We examine the chattering of a rigid body hitting a stationary rigid plane. It is assumed that several points of the object reach the plane almost simultaneously inducing a rapid sequence of impacts, during which the effect of external forces other than the contact forces is negligible. The analysis of a chattering rod by Goyal and others revealed that they undergo CC or they leave the surface after a finite sequence of impacts (incomplete chatter). The exact conditions of these two types of behaviour were determined analytically. We seek analogous conditions for objects with more than 2 potential contact points. The difficulty of the general problem lies in that these systems - unlike the rod - may undergo irregular impact sequences. We use and extend the recently developed theory of common invariant cones of linear operators to develop sufficient conditions of CC. Numerical simulations indicate that our sufficient condition is sharp in many situations. Potential engineering applications including spacecraft landing under microgravity and earthquake protection are outlined.

Tamás Baranyai
PhD student, Dept. of Mechanics, Materials and Structures
Budapest University of Technology and Economics (Hungary)
baranyai@szt.bme.hu

Peter L. Varkonyi
Budapest University of Technology and Economics
vpeter@mit.bme.hu

PP2

Closed-Form Solutions and New Algorithm for Two-Dimensional Frictional Problems

We've presented closed-form solutions for two-dimensional frictional problem loaded by constant external loads. These solutions define the response during the slip period including the exact time and position of the transition from slip to stick. By assuming that the external loads can be treated as constant if the time during is sufficiently small, we proposed a new numerical algorithm for two-dimensional frictional problems excited by time-varying external loads. We also developed an analytical patch for the recommencement of slip after stick, since zero initial velocity at the boundary of friction circle results in difficulties for both analytical and numerical solutions. In order to identify the states of stick and slip, we introduced a two-state boolean variable **B** with **B**=0,1 indicating stick and slip respectively. We utilized this variable step-size algorithm to obtain the response of the system during dynamic slip periods including an accurate determination of the time and position of slip/stick transitions. We've presented numerical examples of two-dimensional problems involving multi-stops to evaluate the performance of the numerical algorithm. The results show much more realistic behaviour in the neighbourhood of slip/stick transitions, and the new algorithm is also significantly more efficient computationally than the conventional method when time steps are chosen so as to

ensure comparable levels of precision.

Jim Barber
University of Michigan
jbarber@umich.edu

PP2

Glycinergic Neurons in the Pre-Bötzinger Complex Are Crucial for Eupnea: An Optogenetic Study

The core structures of the respiratory central pattern generator (CPG) are the pre-Bötzinger (pBC) and Bötzinger (BC) complexes. Synaptic inhibition in these CPG circuits has been proposed to be essential for the eupneic respiratory pattern. We employed viral vectors to express channelrhodopsin (ChR2) or archaerhodopsin (Arch) under control of the glycine transporter 2 promoter in the pBC of Wistar rats. Optoexcitation of pBC glycinergic neurons significantly increased respiratory frequency due to the loss of E2. Optoinhibition also increased the respiratory frequency, but unlike optoexcitation, activation of Arch suppressed the post-I phase. We used an established computer model of the respiratory CPG to mechanistically explain these results. In the model, we found that similar perturbations could be induced by altering the activity of the inhibitory population of pBC inspiratory neurons. Simulated excitation of this population suppressed the BC E2 neurons and augmented oscillation frequency. Inhibiting this population disinhibited post-I and E2 expiratory populations causing tonic discharge, thus eliminating phasic post-I activity and creating conditions for endogenous bursting of excitatory inspiratory neurons at a higher respiratory frequency. We demonstrated the functional importance of glycinergic interneurons in the pBC for generation of the eupneic pattern and provided mechanistic insights for these responses using mathematical modeling.

William H. Barnett
Neuroscience Institute
Georgia State University
wbarnett2@gsu.edu

Yaroslav Molkov
Department of Mathematics & Statistics
Georgia State University
ymolkov@gsu.edu

Ana Abdala, Beihui Liu
School of Physiology
University of Bristol
ana.abdala@bristol.ac.uk, bh.liu@bristol.ac.uk

Davi Moraes
Department of Physiology
University of Sao Paulo
davimoraes@rfi.fmrp.usp.br

Sergey Kasparov, Lucas Koolen
School of Physiology
University of Bristol
sergey.kasparov@ bristol.ac.uk, lk15388@bristol.ac.uk

Jeffrey Smith
Cellular and Systems Neurobiology Section
NIH
smithj2@ninds.nih.gov

Julian Paton
School of Physiology
University of Bristol
julian.f.r.paton@bristol.ac.uk

PP2

Particle Diffusion and Competitive Receptor Binding

We consider a setup in which N particles are initially released into an environment and diffuse freely. Much of the domain boundary is absorbing, where the particles can escape the domain. The rest of the boundary consists of patches that we call “receptors” and that can switch between being reflecting and absorbing. An absorbing receptor turns reflecting (“unavailable”) once a particle collides with it; a reflecting receptor turns absorbing (“recharges”) spontaneously after spending a random exponentially distributed amount of time in the reflecting state. We are interested in the distribution of the number of particles that are absorbed by the receptors. We find that the number of the receptor-absorbed particles has an upper-bound of the order of $(\log N)$. By using a Markov chain approximation in a special case, we also estimate the complete distribution of the number of the receptor-absorbed particles, and find that it matches simulation results in one- and two- dimensional environments. Finally, we use our approach to model synaptic cleft, and find that variability in the number of postsynaptic bindings is strongly affected by the recharging time of the receptors, and only weakly by the number of molecules released. We also find that localization of receptors in clusters and directly across from the release site allows for faster and more reliable onset of the postsynaptic response, especially for slowly recharging receptors.

Alla Borisyuk
University of Utah
Dept of Mathematics
borisyuk@math.utah.edu

Gregory A. Handy
University of Utah Mathematics Department
handy@math.utah.edu

Sean Lawley
Duke University
lawley@math.utah.edu

PP2

Improving Network Inference of Oscillatory Systems: The Impact of False Positive and False Negative Conclusions About the Presence Or Absence of Links

Many research groups have focused on the inference of networks from data such as brain networks from observed EEG. Brain networks but also others are typically classified into main prototypic networks, e.g., Erdos-Renyi, Small World and Scale Free Networks. Two challenges are particularly important: to reliably obtain links in a network and to use network characteristics to uniquely determine the type of network. The correct reconstruction of networks is hampered by mis-estimation of links due to statistical uncertainties, unobserved processes, noise contamination to name just a few. Mis-estimated links in a network typically alter the key characteristics. We investigate to which extent classical statistical approaches to estimate links in a network are reliable; furthermore, we investigate if common rules of type I and II errors should be modified to achieve superior inference. Our approach is based on the topological analysis of the detected networks taking into account the role of two important parameters: false positive and false negative decisions about the presence of links. We present simulation results showing that typical alpha values for statistical inference are suboptimal when, e.g., the degree distribution is to be estimated. We suggest a novel procedure to optimally balance false positive and negative conclusions. This enables us to obtain, e.g., better estimates for the average shortest path length or the degree distribution.

Gloria Cecchini
University of Aberdeen
r01gc15@abdn.ac.uk

Bjoern Schelter
Institute for Complex Systems and Mathematical Biology
b.schelter@abdn.ac.uk

Marco Thiel
University of Aberdeen
Scotland
m.thiel@abdn.ac.uk

Linda Sommerlade
Institute for Complex Systems and Mathematical Biology
University of Aberdeen
l.sommerlade@abdn.ac.uk

PP2

Partial Synchronization in Pulse-Coupled Oscillator Networks

We consider N leaky-integrate-and-fire oscillators coupled by a sum of α-function pulses (whose shape depends on a delay time τ) weighted by a coupling parameter K. Significant insight can be gained when the oscillators are identical, and identically coupled in an all-to-all network. Previous studies have revealed how the stability of the fully synchronous and the fully asynchronous splay states depend on the value of τ, and the sign of K (inhibition vs excitation). We focus on understanding the stability of new classes of attractors describing other stable oscillator configurations that are typically partially synchronized. This includes $(N-1,1)$ states (where $N-1$ oscillators fire in sync and the remaining outlier fires at at different phase), clustered splay states (composed of equal size subsets of synchronized oscillators with the relative phases between clusters organized in a splay configuration) as well as limit cycle states. We analyze the bifurcations between all fixed points and limit cycles for small N. Of particular interest is how long this stability persists when the idealization of identical oscillators and the identical coupling network is relaxed.

Bolun Chen, Jan Engelbrecht
Department of Physics, Boston College
bolun.chen@bc.edu, jan@bc.edu

Renato Mirollo
Department of Mathematics, Boston College
mirollo@bc.edu

PP2

Axonal Transport in Cells: Modeling of Motor-Cargo Dynamics

Intracellular transport along the axons by molecular motors is a crucial component for long distance transfer of cargo inside neurons. We mathematically model the movement of a motor-cargo complex along a parallel arrangement of microtubules. The first passage time for a diffusing motor to reattach to a microtubule is computed, and key quantities of interest are derived with a macroscopic viewpoint of effective transport process over multiple motor attachment and detachment events.

Abhishek Choudhary
Rensselaer Polytechnic Institute
abhi.achoudhary@gmail.com

PP2

Noise-Induced Stabilization of Collective Behavior in Oscillatory Ensembles

We study the role of noise in the emergence of non-trivial collective dynamics of coupled oscillators. Contrary to the standard expectation that noise contributes to destabilize or to smooth out coherent patterns, we discuss some examples where a weak noise can stabilize a collective state: the so-called self-consistent partial synchrony. This regime is characterized by a smooth non-uniform distribution of the phases of the single oscillators, where the frequency of the mean field differs from that of the single units. In a simple, noiseless, biharmonic Kuramoto-Daido setup, self-consistent partial synchrony can be found in a finite range of parameter values, but it is not everywhere stable. Numerical simulations of large ensembles show that a small amount of noise acting on each oscillator can reinstate partial synchrony. We study the phenomenon at a macroscopic level by transforming the noiseless nonlinear continuity equation into a suitable Fokker-Plank equation and solving it by means of a perturbative approach. The corresponding linear stability analysis reveals the overall bifurcation scenario, separating the region where partial synchrony is stable from that where the asynchronous dynamics prevails. The results are in close agreement with microscopic simulations. A similar situation is observed in an ensemble of weakly coupled Rayleigh oscillators, suggesting that the above instance about noise is not isolated.

Pau Clusella Cobero
University of Aberdeen
Universita di Firenze
pau.clusella@abdn.ac.uk

Antonio Politi
University of Aberdeen, UK
a.politi@abdn.ac.uk

PP2

Developing a Hybrid Model for Chemotactically Driven Neuritogenesis

Here we introduce a model for chemotactically-driven neuritogenesis. Neuritogenesis, or neurite outgrowth, is a process in which neurons send out finger-like subcellular structures through cytoskeletal rearrangements. It is an important step in many neural processes, including nerve formation and development, as well as nerve regeneration and injury response. It is known that neurite outgrowth can be influenced by chemotactic gradients, but few models for these processes have been developed. We present a 2D spatial hybrid model, using a PDE diffusion model for the neuropeptides that stimulate neuritogenesis, and a simple, phenomenological agent-based model for the neurite outgrowths. The neurite submodel is simulated using the gradient provided by the diffusion model as an input, and in turn secretes and removes neuropeptide in the PDE submodel. We provide an overview of the model development and several simulation results using a range of physiologically based neuropeptide and neurite configurations.

Jeremy P. D'Silva
University of Michigan School of Public Health
jpdsilva@umich.edu

Marisa Eisenberg
University of Michigan
marisae@umich.edu

PP2

Numerical Solutions of Three Dimensional Telegraphic Equations Using Differential Quadrature Method

This paper employs a novel differential quadrature scheme with B-spline basis functions, that can be used for solving linear and nonlinear partial differential equations in higher dimensions. B-spline functions are employed for space variable and their derivatives. The partial differential equation results into a system of first-order ordinary differential equations (ODEs). The obtained system of ODEs has been solved by a fourth stage Runge-Kutta method. Efficiency and reliability of the method has been established with five linear problems and one nonlinear test problem. Obtained numerical solutions are found to be better as compared to those available in the literature. Simple implementation, less complexity and computational inexpensiveness are some of the main advantages of the scheme. Further, the scheme gives approximations not only at the knots but also at all the interior points in the domain under consideration. The scheme is found to be providing convergent solutions and handles different cases. The stability of the scheme is dependent on the time step condition used by the four stage strongly stable Runge-Kutta method. However, when we apply stability analysis for the scheme derived, it is found to be unconditionally stable. The scheme can therefore be used effectively to handle higher dimensional PDEs.

Sumita Dahiya
Indian Institute of Technology Roorkee, India
sumita.iitr@gmail.com

Ramesh Mittal
Indian Institute of Technology, Roorkee
mittalrc@gmail.com

PP2

Observation Impact in Data Assimilation for Flood Inundation Forecasting

Accurate flood inundation forecasting provides vital information, enabling local residents and emergency services to make necessary preparations. Data assimilation is a powerful technique for combining forecasts from mathematical models with observations to give an improved forecast. In this study, numerical inundation simulations are carried out in a river channel topography using Clawpack. Data assimilation is performed using an Ensemble Transform Kalman Filter (ETKF) and synthetic observations of water depth in identical twin experiments. In agreement with other studies, we find that using data assimilation to combine observations of water depth with forecasts from a hydrodynamic model works very well at the time of the observations, but that the observation impact is short-lived. The forecast errors quickly increase to the level of a free-running forecast with no assimilation. We show that the time taken for the forecast to lose the added skill from the assimilation of observations depends on the length of the domain of interest. This is because the assimilation corrects water depths in all parts of the domain (even those which are unobserved) and error growth in the forecast step propagates downstream. We demonstrate that this pattern of error growth can be due to incorrect friction parameter specification, rather than errors in upstream inflow. Joint state-parameter estimation leads to an improvement in the forecast skill, and is less dependent on domain length.

Sarah Dance
University of Reading
s.l.dance@reading.ac.uk

Elizabeth Cooper
University of Reading, UK
e.s.cooper@pgr.reading.ac.uk

Javier Garcia-Pintado
MARUM
University of Bremen, Germany
jgarciapintado@marum.de

Nancy K. Nichols
University of Reading
Department of Mathematics
n.k.nichols@reading.ac.uk

Polly Smith
University of Reading, UK
p.j.smith@reading.ac.uk

PP2

Synaptic Plasticity in Excitatory and Inhibitory Hippocampal Neuron Circuit Dynamics

Microcircuits of inhibitory and excitatory neurons in the hippocampus have been studied over the past 30 years because of their importance in creating neural spike rhythms that have been implicated in processes such as the consolidation of episodic memories. Models for these circuits range from extremely simple (coupled phase oscillators) to extremely complex (complete, spatially extended, biophysically correct representations of the cells in Neuron). Various complex phenomena have been observed and explained through these models, such as synchronization, phase precession and bursting. Here we consider how time dependent connectivity of these cells effects these phenomena by incorporating a model for short-term synaptic plasticity that we developed and parameterized (from whole cell experiments) for two specific interneuron-pyramidal cell connections. To make analysis possible, we use the maps to describe both the plasticity and spike timing in the circuit (inspired by the work of Ermentrout and Kopell, 1998).

Claire Seibold
University of Montana
claire.seibold@umontana.edu

Dominika Dec
Dept. of Mathematical Sciences
dominika.dec@umontana.edu

Emily F. Stone
Dept. of Mathematical Sciences

The University of Montana
stone@mso.umt.edu

PP2

Determining the Mean Field Dynamics in Complex Networks Via the Kramers-Moyal Expansion

Populations of phase-coupled oscillators can exhibit a variety of qualitatively different dynamics. The settings in which these dynamics can be determined analytically are rather limited to special symmetries and comparably simple frequency distributions. In the current work we recover the dynamics of such populations from the time series of some common variables (e.g., mean fields). We employ the Kramers-Moyal expansion that capitalizes on the conditional cumulants of these variables [R. Friedrich, J. Peinke, PRL 1997; J. Gradisek, S. Siegert, R. Friedrich, I.I. Grabec, PRE 2000]. After testing for Markovianity and the applicability of the Pawula theorem (to guarantee the diffusive characters of the dynamics) we focus on the so-called drift coefficient that represents the deterministic part of the dynamics. We illustrate the accuracy of the method exploring a two-dimensional case including the dynamics of the mean phase and the phase divergence. These variables are seminal for studying a system of phase-coupled oscillators with bimodal frequency distributions or its equivalent of two interconnected network system [B. Pietras, N. Deschle, A. Daffertshofer, PRE 2016]. After this illustration we apply the method to cases were analytical results are not present. For this we break symmetry by imposing a different network topology in one of the two networks and show that the Kramers-Moyal expansion can yield is a meaningful, analytical description of the mean field dynamics.

Nicolás Deschle
MOVE & iBB, Vrije Universiteit Amsterdam
ICSMB, Univesity of Aberdeen
n.deschle@vu.nl

Björn Schelter
Institute for Complex Systems and Mathematical Biology
University of Aberdeen, UK
b.schelter@abdn.ac.uk

Andreas Daffertshofer
MOVE Research Institute Amsterdam
VU University Amsterdam
a.daffertshofer@vu.nl

PP2

Spectral Properties of Spiral Waves in the Barkley Model

Spectral properties of spiral waves formed in the Barkley model are investigated. Absolute spectra, essential spectra, and pseudospectra of spirals are calculated using asymptotic wave trains. These results are compared with the point spectra of spirals on large disks. The spirals are computed by numerical continuation, and point spectra by iterative methods.

Stephanie Dodson
Brown University
Stephanie_Dodson@Brown.edu

Bjorn Sandstede
Division of Applied Mathematics
Brown University
bjorn_sandstede@brown.edu

PP2

Large Time Behavior of a Conserved Phase-Field System

We investigate the large time behavior of a conserved phase-field system

$$\begin{aligned} \tau\phi_t - \Delta(\delta\phi_t - \Delta\phi + g(\phi) - u) = 0, \\ epsilon u_t + \phi_t - \Delta u = 0, \end{aligned}$$

which describes phase separation in a material with viscosity effects, and occupying a bounded domain $\Omega \subset R^d$, $d = 1, 2, 3$. $\tau > 0$ is a relaxation time, $\delta \geq 0$ is the viscosity parameter, $\epsilon \geq 0$ is the heat capacity, ϕ is the order parameter, u is the absolute temperature and $g = G'$, where G is a double-well potential. We prove a well-posedness result. Also, on the levels of global attractor, exponential attractors and inertial manifolds, we establish the convergence of the dynamics of this system to those of the well known viscous Cahn-Hilliard equation, as the heat capacity goes to zero, i.e., $\epsilon \to 0$. This work extends and improves in an interesting way, some recent results in this direction.

Cyril D. Enyi
King Fahd University of Petroleum and Minerals.
enyicyrildennis@gmail.com

PP2

Exploring the Risk of Desynchronization in Complex Networks

In the field of Complex Network Synchronization an unexplored notion is that of the risk of desynchronization. The risk of desynchronization is a quantity related to the size of the basin of synchronization and a quantity which is easily understood within the context of coupled oscillators. The risk of desynchronization is a measure of how likely a particular node, or a set of nodes, within a network is to cause desynchronization upon perturbation away from the synchronous state. The concept of risk of desynchronization leads to several questions; how is the risk related to the number of nodes perturbed within the network? What is the relationship between the risk and the degree of a particular node in the network? Is the risk of desynchronization related to the size of the perturbation? We will now examine these questions, beginning with some theory.

Jeremie A. Fish
Clarkson University
fishja@clarkson.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

PP2

Measurement Sequences and Chernoff Information

First, I illustrate how a Bayesian analysis can guide measurement selection for a short sequence of measurements for a contrived example. Then I extend the small sample analysis that requires priors and costs to an asymptotic analysis that provides a comparative valuation independent of priors and costs. While the motivating examples and analysis are novel, the conclusions match work of Chernoff in 1952.

Andrew M. Fraser
Los Alamos National Laboratory
andy@fraserphysics.com

PP2

Parameter Estimation for Dynamical Systems Using Bifurcation Analysis

Dynamical systems are widely used to model real world systems in biology, physics, finance, and many engineering applications. This work builds on existing methods of parameter estimation and uncertainty quantification by extending them to make use of information from bifurcation analysis. After performing structural and practical identifiability analysis of various systems, we compare the efficiency of parameter estimates before and after leveraging the bifurcation structure.

Jace E. Gilbert
University of Nevada, Reno
Mathematics and Statistics
Jace_Gilbert@nevada.unr.edu

Paul J. Hurtado
Mathematical Biosciences Institute
The Ohio State University
phurtado@unr.edu

PP2

Saddle Slow Manifolds and Canard Orbits in the Hodgkin-Huxley Model

Many physiological phenomena have the property that some variables evolve much faster than others. For example, neuron models typically involve observable differences in time scales. The Hodgkin-Huxley model is well known for explaining the ionic mechanism that generates the action potential in the giant squid axon. Rubin and Wechselberger nondimensionalized this model and obtained a singularly perturbed system with two fast, two slow variables, and an explicit time-scale ratio parameter. The dynamics of this system are very complex and feature periodic orbits with a series of action potentials separated by small-amplitude oscillations; also referred to as mixed-mode oscillations. The system features two-dimensional locally invariant manifolds called slow manifolds, which can be either attracting or of saddle type. We introduce a new method for computing two-dimensional saddle slow manifolds. This allows us to show how the interaction of slow manifolds creates a new mechanism for robust maximal canard orbits, which play an important role in organizing mixed-mode oscillations and determining the firing rates of action potentials.

Cris Hasan
University of Auckland
cris.hasan@auckland.ac.nz

Hinke M. Osinga, Bernd Krauskopf
University of Auckland
Department of Mathematics
H.M.Osinga@auckland.ac.nz, b.krauskopf@auckland.ac.nz

PP2

Clustered Ventilation Defects in Asthmatics

Asthma is a chronic lung disease of reversible airway constriction, and during an asthma attack we see heterogeneous ventilation, or specifically, clustered ventilation defects. These effects are seen in imaging studies of lungs in asthmatics during asthma attacks in the form of the images showing clustered regions of very low ventilation, which is expected from a person struggling to draw breath, but interestingly, the images also show hyper-ventilated regions. These clusters vary from event to event, even in the same subject, and thus, it is believed that the causes are dynamic rather than structural. We want to understand the dynamic mechanisms behind the formation of these ventilation clusters, both in terms of the underlying mathematics and the physiological implications. Mechanisms of spatial clustering have been suggested, and we use these concepts to help us formulate and analyse models representative of the formation of clustered ventilation defects. In particular we decompose the problem two kinds of airway coupling. This poster looks at these two different coupling styles and the results we get from each one, being particularly interested in how each model can lead to clustered ventilation.

Austin J. Ibarra
University of Auckland
Department of Mathematics
aj.ibarra001@gmail.com

PP2

Mathematical Tales of Fairy Circles

Dryland ecosystems exhibit intriguing self-organising mechanisms in order to account for the strong plant competition for limited resources, especially water. These mechanisms typically manifest themselves in the form of vegetation patterns, ranging from bare-soil gaps in uniform vegetation to vegetation stripes and vegetation spots. The underlying mathematical model that describes these patterns is of singularly perturbed reaction-diffusion type. A fascinating example of gap patterns is the so-called fairy circle phenomenon, found in Namibia and recently in Australia.Fairy circles are circular barren gaps in grasslands of significant size, a few meters in diameter, that form nearly-periodic patterns on large, landscape scales. Mechanisms for the appearance of this phenomenon in Namibia and in Australia, and corresponding reaction-diffusion models, have recently been proposed by Zelnik et al. [PNAS(2015)] and by Getzin et al. [PNAS(2016)]. Unlike the more widely studied homoclinic pulse-type vegetation patterns, fairy circles have an underlying multi-front structure. This poster presents a mathematical analysis of the model proposed for Namibian fairy circles. The mathematical approach is along the lines of geometric singular perturbation theory and is accompanied by numerical simulations of the full model.

Olfa Jaibi
Univeristeit Leiden
o.jaibi@math.leidenuniv.nl

Martina Chirilus-Bruckner
University of Leiden
Mathematical Institute
m.chirilus-bruckner@math.leidenuniv.nl

Arjen Doelman
Mathematisch Instituut
doelman@math.leidenuniv.nl

Ehud Meron
Ben-Gurion University
ehud@bgu.ac.il

PP2

High-Order Finite-Difference Time-Domain Simulation of Electromagnetic Waves at Complex Interfaces Between Dispersive Media

We propose a new numerical scheme for the simulation of electromagnetic waves in linear dispersive media, materials where the permittivity depends on the frequency of the wave. We formulate Maxwell's equations as a second order wave equation with an additional time-history term which is associated with the macroscopic electronic response of the material to the external electric field. This formulation allows us to address material interfaces with complex curvilinear geometries, thereby avoiding the drawbacks of the well-known staggered Yee numerical discretization. We use the physical interface conditions and boundary conditions for Maxwell's equations to develop numerical compatibility conditions which preserve the accuracy and stability of the scheme at the interfaces and boundaries. High accuracy simulation of transient waves at dispersive material interfaces is of particular interest in the fields of plasmonic metamaterials and nano-photonics, with various applications in imaging and sensing. This is joint work with Jeffrey W. Banks and William D. Henshaw.

Michael Jenkinson
Rensselaer Polytechnic Institute
Department of Mathematical Sciences
mikejjenkinson@gmail.com

PP2

Torus Bifurcation in Purkinje Cell

Purkinje cell is an important kind of neuron in the cerebellum. Recently, the cell was found to have amplitude-modulation spiking characters in the experiments. This phenomena can be explained by torus bifurcation from dynamic system view, which will be shown in this poster.

Huiwen Ju
Neuroscience Institute
Georgia State University
hju5@student.gsu.edu

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

Alexander Neiman
Ohio University
Department of Physics and Astronomy
neimana@ohio.edu

PP2

A Hamiltonian Formulation for the Estimation of Partially Observed Chaotic Systems

The problem of tracking hidden states in nonlinear dynamical systems is confronted in a variety of contexts, from geophysics to plasmas to neuroscience. For linear systems, this estimation is solved exactly via the Kalman filter, but nonlinear systems demand either linearizing approximations or statistical representations. Recent improvements in nonconvex optimization have led to adopting methods that instead treat the estimation in a variational approximation, thereby casting the sequential filtering problem as a global minimization. In continuous time, the variational approximation arises as the stationary phase approximation of a path integral, analogous to transition amplitudes in mechanics. Carrying this analogy further, the formulation admits an action functional $A[x(t)]$ and associated Lagrangian $\mathcal{L}(x, \dot{x}, t)$, which can be used to derive Euler-Lagrange equations with natural boundary conditions. Alternatively, the optimal estimate can be calculated by transforming to a Hamiltonian space, the idea being that the constraints provided by symplectic symmetry will improve estimation accuracy. Since symplectic structure also arises quite naturally in discrete Lagangian systems, the implications of this symmetry are compared in both Lagrangian and Hamiltonian formulations for a sparsely observed chaotic model. It is found that working in Hamiltonian coordinates can in some cases considerably improve the accuracy of the optimal estimate.

Nirag Kadakia, Daniel Rey, Jingxin Ye
University of California San Diego
nkadakia@physics.ucsd.edu, nadrey@gmail.com,
j9ye@physics.ucsd.edu

Henry D. Abarbanel
Physics Depratment
Univ of California, San Diego
habarbanel@ucsd.edu

PP2

Consensus in One and Two Population Models of Opinion Dynamics

We consider a continuous version of the Krause model of opinion dynamics. As per the model, agents update their opinions, which are one-dimensional, based on a compactly supported interaction function. Interaction between agents either leads to a state of consensus, where agents starting out with differing initial opinions converge to a single opinion as time evolves, or to a fragmented state with multiple opinions. We linearize the system about a uniform density solution and predict consensus or fragmentation based upon the most unstable mode of the dispersion relation, which is then compared against numerical simulations for varying domain sizes and interaction functions. We then extend our model to two populations, each having a distinct interaction function, and test our hypothesis developed for the single population model.

Ratna Khatri
Department of Mathematical Sciences
George Mason University
rkhatri3@masonlive.gmu.edu

PP2

Topological Principles of Control in Dynamical Networks

Networked biological systems, such as the brain, feature complex patterns of interactions. To predict and correct the dynamic behavior of such systems, it is imperative to understand how the underlying topological structure affects and limits the function of the system. Here, we use

network control theory to extract topological features that favor or prevent network controllability, and to understand the network-wide effect of external stimuli on large-scale brain systems. Specifically, we treat each brain region as a dynamic entity with real-valued state, and model the time evolution of all interconnected regions using linear, time-invariant dynamics. We propose a simplified feed-forward scheme where the effect of upstream regions (drivers) on the connected downstream regions (non-drivers) is characterized in closed-form. Leveraging this characterization of the simplified model, we derive topological features that predict the controllability properties of non-simplified networks. We show analytically and numerically that these predictors are accurate across a large range of parameters. Among other contributions, our analysis shows that heterogeneity in the network weights facilitate controllability, and allows us to implement targeted interventions that profoundly improve controllability. By assuming an underlying dynamical mechanism, we are able to understand the complex topology of networked biological systems in a functionally meaningful way.

Jason Kim
University of Pennsylvania
jinsu1@seas.upenn.edu

Fabio Pasqualetti
Department of Mechanical Engineering
University of California, Riverside, CA
fabiopas@engr.ucr.edu

Danielle S. Bassett
School of Engineering and Applied Science
University of Pennsylvania
dsb@seas.upenn.edu

PP2

The Acceleration and Deceleration of Mixing Rates by Discontinuities in Chaotic Flows

Studies on the rate of mixing in highly viscous fluids have primarily been concerned with time dependent smooth deformations. A well-known phenomena in non-uniformly hyperbolic systems with diffusion is the emergence of strange eigenmodes with exponential decay rate. Yet mixing devices or fluid properties may allow for the introduction of discontinuities, the dynamics of which are more subtle and less understood. We present a model combining the mechanisms of stretching, cutting, and shuffling, in which the presence of diffusion reveals time periodic eigenfunctions whose decay rates show unexpected sensitivity to the governing parameters.

Hannah E. Kreczak, Rob Sturman, Mark Wilson
University of Leeds
mm10hek@leeds.ac.uk, r.sturman@leeds.ac.uk, m.wilson@leeds.ac.uk

PP2

Reaction Front Barriers in Unsteady Fluid Flows

Many chemical and biological systems can be characterized by the propagation of a front within an underlying fluid flow. One approach to formalizing a general theory is to apply frameworks developed in nonlinear dynamics. It has been shown that invariant manifolds form barriers to passive transport in time-dependent or time-periodic fluid flows. More recently, analogous manifolds termed burning-invariant-manifolds (BIMs), have been shown to form one-sided barriers to reaction fronts in advection-reaction-diffusion (ARD) systems. To model more realistic time-aperiodic or unsteady flows, recent theoretical work has suggested that similar one-sided barriers, termed burning Lagrangian coherent structures (bLCSs), exist for fluid velocity data prescribed over a finite time interval. In this presentation, we use a stochastic wind to generate time dependence in a double-vortex channel flow and demonstrate the (locally) most attracting or repelling curves are the bLCSs.

Rory A. Locke
UC-Merced
rlocke@ucmerced.edu

Kevin A. Mitchell
University of California, Merced
Physics
kmitchell@ucmerced.edu

PP2

Inference and Comparison of Dynamical Systems As Models for Glacial Climate Variability

The most pronounced variability in the climate during the last glacial period are the so-called Dansgaard-Oeschger (DO) events. These abrupt climate changes are elusive in simulations of state-of-the-art coupled climate models. Furthermore, the underlying dynamical mechanism remains unknown. We investigate whether the climate system is exhibiting self-sustained oscillations of vastly varying periods or rather noise-induced jumps in between two quasi-stable regimes. To this end, we employ statistical model comparison to compare different classes of stochastic dynamical systems, representing different dynamical paradigms, to the NGRIP ice core record from Greenland. We avoid calibrating the models by time series fitting, but rather focus on the most important qualitative features of the data, as captured by summary statistics. These are used to perform inference and comparison of the models via Approximate Bayesian Computation. Based on our choice of summary statistics, we find evidence that simple stochastic motion in a double well potential is better supported by the data than noisy relaxation oscillations or excitable systems. With our model comparison approach we furthermore investigate to which extent the dynamical process underlying the observed climate record can be regarded as stationary.

Johannes Lohmann, Peter Ditlevsen
Centre for Ice and Climate, Niels Bohr Institute
University of Copenhagen, Denmark
lohmann.johannes@googlemail.com, pditlev@nbi.ku.dk

PP2

A Variant of the Aubry-André Model for Granular Materials

We study linear and nonlinear modes in granular crystals with an incommensurate Aubry-André (AA) potential. We introduce an on-site external potential in each particle in the form of a harmonic oscillator with elastic constant k_n, and we set $k_n = \gamma f_n$ with $f_n = \cos(2\pi\xi n + \phi)$. We show that, an AA localization transition can be induced in granular crystals, as it is in Schrödinger chains, by the action of the external potential. We also explore the different families of nonlinear modes that emerge and their stability.

Alejandro J. Martinez

Mathematical Institute
University of Oxford
martinez@maths.ox.ac.uk

Mason A. Porter
University of Oxford
Mathematical Institute
mason@math.ucla.edu

Panayotis Kevrekidis
Department of Mathematics and Statistics
University of Massachusetts
kevrekid5@gmail.com

PP2

A Heterodimensional Cycle in the Flow of a 4D Differential Equation

We investigate a four-dimensional ordinary differential equation model for intracellular calcium dynamics. This model exhibits a heterodimensional cycle, which is a heteroclinic connection between two saddle-periodic orbits whose corresponding stable manifolds are of different dimensions. Heterodimensional cycles are associated with new types of chaotic dynamics in diffeomorphisms of three or more dimensions, and hence in differential equation systems of four or more dimensions. In particular, it has been shown by Bonatti and Diaz that, given a C^1 diffeomorphism containing a codimension-one heterodimensional cycle, there is an arbitrarily C^1-close set of diffeomorphisms that have robust codimension-one heterodimensional cyles. We wish to examine how the heterodimensional cycle in the flow of this differential equation affects the nearby dynamics. To observe the behaviour of this practical example, we require computational tools and visualisation techniques for invariant manifolds of periodic orbits in four dimensions. We present a three-dimensional Poincar section, which provides an overview of the model's behaviour. Projections of the four-dimensional flow into three dimensions are then used to explain the behaviour of objects in the Poincaré section in more depth.

Gemma Mason
Applied and Computational Math
Caltech
g.mason@auckland.ac.nz

Andy Hammerlindl
Monash University
andy.hammerlindl@monash.edu

Bernd Krauskopf, Hinke M. Osinga
University of Auckland
Department of Mathematics
b.krauskopf@auckland.ac.nz, H.M.Osinga@auckland.ac.nz

PP2

Designing a Finite-Time Mixer: Optimizing Stirring for Two-Dimensional Maps

Mixing results from a two part process in which large gradients are created by advection and then smoothed by diffusion. We investigate methods of designing efficient finite-time mixers to optimize stirring of a passive scalar in a two-dimensional incompressible flow. Area preserving maps with parameters that change in time are used to model the pure advection, applied numerically with the Perron-Frobenius method. Mixing is measured via a negative Sobolev seminorm, which simulates the smoothing of high order frequencies by diffusion. We use experimental results and frequency and stability analysis to construct stirring schemes to improve mixing.

Rebecca A. Mitchell
University of Colorado Boulder
rebecca.mitchell089@gmail.com

James D. Meiss
University of Colorado
Dept of Applied Mathematics
jdm@colorado.edu

PP2

Global Invariant Manifolds and Slow Manifolds Near a Singular Hopf Bifurcation

Invariant manifolds of equilibria and periodic orbits are key objects that organize the behavior of a dynamical system both locally and globally. If multiple time scales are present, there also exist so-called slow manifolds, along which the flow is very slow compared with the rest of the dynamics. Slow manifolds are locally invariant objects and they may interact with invariant manifolds, which are globally invariant objects. Little is known about such interactions and we show that they may produce new types of complicated dynamics. To this end, we consider a slow-fast system near a singular Hopf bifurcation and study the transition through a quadratic tangency between the two-dimensional unstable manifold of the associated equilibrium and a two-dimensional repelling slow manifold. We compute the respective manifolds as families of orbits segments with a two-point boundary value problem setup, and track their intersections as a parameter is varied. We describe the local and global properties of the manifolds as they interact, as well as the role of their interactions in organizing large-amplitude oscillations in the dynamics.

Jose Mujica, Bernd Krauskopf, Hinke M. Osinga
University of Auckland
Department of Mathematics
j.mujica@auckland.ac.nz, b.krauskopf@auckland.ac.nz, H.M.Osinga@auckland.ac.nz

PP2

Global Regularity in a Surface Growth Model Using a-Posteriori Methods

We study the time evolution of a surface growth model of the type $\partial_t h = -\Delta^2 h - \Delta|\nabla h|^2$, where standard methods fail to verify global uniqueness and smoothness of solutions. Based on an arbitrary numerical approximation, we apply a-posteriori error-analysis in order to prevent a blow up analytically, which is a method that in a similar way also applies to 3d Navier-Stokes. Here we derive energy-estimates for the error between solution and approximation that yields a scalar ODE controlling the norm of the error and whose coefficients solely depend on the numerical data. Also, the solution of the ODE can be bounded using only numerical data. A key technical tool is a rigorous eigenvalue bound for the nonlinear operator linearized around the numerical approximation. The presented method succeds to show global uniqueness for relatively large initial conditions, which was studied in numerical simulations.

Christian Nolde
Universität Augsburg
christian.nolde@math.uni-augsburg.de

Dirk Blömker
Universitat Augsburg
Germany
dirk.bloemker@math.uni-augsburg.de

PP2

Improving Synchronization Via Adaptive Rewiring in Networks of Kuramoto Oscillators

Synchronization of non-identical oscillators coupled through complex networks is an important example of collective behavior, and many studies examine how the architecture of interactions shapes synchronization patterns. Here, we focus on adaptive networks, where the structure of the network changes in response to the node dynamics. In particular, we use the Kuramoto model to investigate how via a local rewiring rule, an initially random network converges to a topology that supports improved synchronization. The adaptation strategy preserves the total number of edges, and depends only on instantaneous, pairwise phase differences of neighboring nodes. In the case of binary, undirected networks, a local rule that preserves connections between more desynchronized oscillators, and that breaks and rewires connections between more in phase oscillators, can improve synchronization. Furthermore, in line with results from studies on optimal synchronization, throughout adaptation the Laplacian spectra and the relationship between its eigenvectors and the intrinsic frequencies undergo specific changes. Finally, we find that after sufficient adaptation, the resulting network exhibits degree - frequency and frequency - neighbor frequency correlations that have been associated with explosive synchronization transitions. By considering the interplay between structure and dynamics, this work helps elucidate a mechanism through which emergent phenomena can arise in complex systems.

Lia Papadopoulos
University of Pennsylvania
Department of Physics and Astronomy
epapad@sas.upenn.edu

Jason Kim
University of Pennsylvania
jinsu1@seas.upenn.edu

Danielle S. Bassett
School of Engineering and Applied Science
University of Pennsylvania
dsb@seas.upenn.edu

PP2

A Discontinuous Map for a Human Sleep-Wake Network Model Predicts Recovery from Sleep Deprivation

Disrupted sleep schedules can cause desynchronization of the sleep-wake cycle and the 24-hour circadian rhythm. Such desynchronization has been suggested to contribute to several health issues including diabetes, cardiovascular disease, and cancer. In this work, we consider a physiologically-based model for human sleep, namely, a system of differential equations describing the firing rates of neuronal populations promoting sleep and wake states, the circadian rhythm, and the homeostatic sleep drive. To predict recovery from sleep deprivation, we apply a discontinuous map that has been computed from the model and relates the phase of sleep onset (relative to the circadian rhythm) on day n to sleep onset on day n+1. Our results show that small perturbations (e.g., 0-12 hours) in sleep onset timing result in shorter sleep episodes compared to large perturbations (e.g., 18-24 hours past the regular sleep onset time), as suggested by experimental observations. Moreover, the map allows us to predict the length of the sleep and wake episodes during recovery sleep as the sleep-wake cycle regains synchrony with the circadian rhythm.

Sofia H. Piltz
University of Michigan
piltz@umich.edu

Cecilia Diniz Behn
Colorado School of Mines
Applied Math & Statistics
cdinizbe@mines.edu

Victoria Booth
University of Michigan
vbooth@med.umich.edu

PP2

Oscillatory States in Working Memory Model Facilitate Activation and Network Capacity

Working memory is associated with sustained periods of elevated firing rates of neuronal populations. These elevated firing rates may encode different aspects of a memory or different memories altogether, and stimuli must be able to easily activate and inactivate populations in physiologically relevant timescales. We present a neural field network model that incorporates oscillating states under certain parameter regimes. Three timescales (fast excitation, slow inhibition, and slower excitation) allow the network to transition from a low baseline firing rate to oscillatory states when external stimuli are applied. The oscillations facilitate activation and allow for multiple simultaneously active populations in splay-state solutions. By varying the timing of the stimuli we may then select for different network activation orderings and combinations. We numerically continue these solutions to determine their existence and stability as a function of network parameters such as mutual inhibition.

Jason E. Pina
University of Pittsburgh Department of Mathematics
jay.pina@pitt.edu

PP2

Unraveling the Chaos-Land and Its Organization in the Rabinovich System

A suite of analytical and computational techniques based on symbolic representations of simple and complex dynamics, is further developed and employed to unravel the global organization of bi-parametric structures that underlie the emer-gence of chaos in a simplified resonantly coupled wave triplet system, known as the Rabinovich system. Bi-parametric scans reveal the stunning intricacy and intramural connections between homoclinic and heteroclinic connections, and codimension-2 Bykov T-points and saddle structures, which are the prime organizing centers of complexity of the bifurcation unfolding of the given system. This suite includes Deterministic Chaos Prospector (DCP) to sweep and effectively identify regions of simple (Morse-Smale) and chaotic structurally unstable dynamics in the system. Our analysis provides striking new insights into the complex behaviors exhibited by this system, that are hitherto unexplored.

Krishna Pusuluri
Georgia State University
Neuroscience Institute
pusuluri.krishna@gmail.com

Arkady Pikovsky
Department of Physics and Astronomy
University of Potsdam, Germany
pikovsky@uni-potsdam.de

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

PP2

Kernel-Based Lasso for the Inference of Complex Spatial Networks

With increasing supply of data collected from numerous complex systems, a key question is what patterns and properties of the underlying systems can be extracted from such data. A particular such problem is to infer the network structure of interacting components from data, mathematically formulated as an inverse problem. Given that numerous complex networks in real-life are spatially embedded, we ask, can such spatial constraints be exploited (rather than suffered from) to make better inference? An example is the synaptic connections in human brains, which are mostly short-range and have profound impacts on brains neurological dynamics and functionality. Based on the preference of short-range spatial connections, we develop a kernel-based Lasso framework to infer complex spatial networks. We show by numerical experiments that the proposed method improved significantly upon existing network inference techniques. Importantly, such enhancement is achieved even when the exact spatial distribution of the embedded edges is unknown, making the method particularly relevant as a computational tool to efficiently and reliably infer large spatial networks in practice.

Fernando J. Quevedo
206 Outer Main Street APT301
Potsdam NY, 13676
QuevedFJ@Clarkson.edu

Erik Bollt
Clarkson University
bolltem@clarkson.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

PP2

A Model of Localized States in Visual Cortex

Primary visual cortex features a quasiperiodic orientation preference map with a regular length scale. Voltage imaging experiments have shown that local, oriented visual stimuli elicit activation that is orientation-selective and patchy within the stimulus footprint but non-selective outside the footprint. We study the dynamics of these input-driven states in a neural field model with a biologically-motivated radial connectivity profile and sub-populations encoding different orientations. We argue that the observed patchy cortical activation patterns arise in a symmetry breaking from the radial connectivity and that the orientation preference map fixes the spatial phase of such patterns.

James Rankin
New York University
james.rankin@gmail.com

Frédéric Chavane
Institut de Neuroscienes de la Timone (INT)
CNRS & Aix-Marseille University
frederic.chavane@univ-amu.fr

PP2

Synchronized Bursting from Combined Inhibitory and Electrical Coupling in a Neuronal Model

We consider two bursting neurons mutually coupled via both electrical and inhibitory connections. We report a push-pull synchronization mechanism of the combined coupling where electrical and inhibitory connections can synergistically induce robust synchronization, even though by itself electrical coupling induces anti-phase spiking and inhibition is repulsive for a majority of initial conditions. The push-pull mechanism is based on the properties of (i) electrical coupling to stabilize burst- but destabilize spike-synchronization and (ii) inhibition to generally promote anti-phase bursting but stabilize spike synchrony when initial conditions are close. The combined action of the two couplings uses the best of the two worlds to stabilize synchronized bursting. We also show that the duty cycle of the self-coupled system that governs synchronization effectively controls the stability of synchronized bursting.

Reimbay Reimbayev
Department of Mathematics and Statistics
Georgia State University
reimbayev2@student.gsu.edu

Kevin Daley
Georgia State University
kdaley@student.gsu.edu

Igor Belykh
Department of Mathematics and Statistics
Georgia State University
ibelykh@gsu.edu

PP2

Computing Electron Transport Rates Via Classical Periodic Orbits

Electron transport rates in chaotic atomic systems are computable from classical periodic orbits. This technique allows for replacing a Monte Carlo simulation launching millions of orbits with a sum over tens or hundreds of properly chosen periodic orbits using a formula called the spectral determiant. A firm grasp of the structure of the periodic orbits is required to obtain accurate transport rates. We apply a technique called homotopic lobe dynamics (HLD) to understand the structure of periodic orbits to compute the ionization rate in a classically chaotic atomic system, namely the hydrogen atom in strong parallel electric and magnetic fields. HLD uses information encoded in the intersections of stable and unstable manifolds of a few orbits to compute relevant periodic orbits in the system. All unstable periodic orbits are computed up to a given pe-

riod, and the ionization rate computed from periodic orbits converges exponentially to the true value as a function of the period used. We then use periodic orbit continuation to accurately compute the ionization rate when the field strengths are varied over a range of parameter where the structure of the periodic orbits remains constant, and no periodic orbits are born or lost in a bifurcation. Then, by using the same periodic orbits and computing their Maslov indices, semiclassical spectral determinant is used to compute semiclassical resonances for the system.

Sulimon Sattari
University of California, Merced
School of Natural Sciences
ssattari2@ucmerced.edu

PP2

Droplet Motion for the Stochastic Cahn-Hilliard Equation

We study the stochastic Cahn-Hilliard equation, which is a model describing the phase seperation and subsequent coarsening of binary alloys. The infinite dimensional stochastic dynamics is given by the motion along a finite dimensional slow manifold. In particular, we consider the dynamics of bubble solutions that is almost spherical interfaces. We derive the effective equation on the slow manifold and show stochastic stability.

Alexander Schindler
Universität Augsburg
alexander.schindler@math.uni-augsburg.de

Dirk Blömker
Universitat Augsburg
Germany
dirk.bloemker@math.uni-augsburg.de

PP2

Model of Dendronotus Iris Swim Cpg Circuit

We propose a detailed model to study robust network bursting activity recorded in the swim central pattern generator of the sea slug Dendronotus Iris. The neural circuit consists of calibrated Hodgkin-Huxley type model forming two pairs of half-center oscillators, which are coupled by inhibitory and excitatory alpha and dynamic synapses, along with gap junctions. We also discuss a mathematical abstraction of such a network.

Andrey Shilnikov
Neuroscience Institute and Department of Mathematics
Georgia State University
ashilnikov@gsu.edu

Deniz Alacam
Georgia State University
Mathematics Department
dalacam1@student.gsu.edu

Jack Scully
Georgia State University
jamesjscully@gmail.com

PP2

Validated Computations for Heteroclinic Orbits Between Hyperbolic Equilibria for ODEs

In this talk we present a computer-assisted procedure for proving the existence of transverse heteroclinic orbits between hyperbolic equilibria for polynomial vectorfields. The idea is to compute high-order Taylor approximations of local charts on the (un)stable manifolds by using the Parameterization Method and to use Chebyshev series to parameterize the orbit in between. The existence of a heteroclinic orbit can then be analyzed by setting up an appropriate fixed-point problem amenable to computer-assisted analysis. In addition, we explain how this scheme can be used to perform validated continuation. This is joint work with Jan Bouwe van den Berg and Christian Reinhardt.

Ray Sheombarsing
VU University Amsterdam
R.S.S.Sheombarsing@vu.nl

PP2

The Effect of Latent Confounding Processes on the Estimation of the Strength of Casual Influences in Chain-Type Networks

Reliable recognition of casual interactions between processes is an issue prevalent in applications of dynamical systems. When the structure of a network is not a priori known it is almost impossible to observe and measure all components of a system. Missing components could lead to the appearance of false - or spurious - interactions. The aim of this study is to demonstrate the effect of missing components of a network on the inferred strength of a spurious interaction. In cases where a hidden process - or latent confounder - is influencing a network and a spurious interaction appears, it is not possible to rely on estimates of the strength of this link as corresponding estimation methods are influenced by the latent confounder. This study demonstrates how a latent confounder affects the inferred strength of a causal connection between two processes based on vector autoregressive models. In summary, while it is possible to measure the strength of directed causal influences between processes, the estimation of strength can be confounded if components of a system are not observed. Consequently, unless a network inferred from data is free from latent confounders, any inferred causal connection could be spurious. As we will show, the estimated strength of a spurious link is influenced by a latent confounder and cannot be relied upon. This is true of various measures of the strength of Granger causal influences in which any delayed interaction is treated as casual.

Helen Shiells
University of Aberdeen
r01hcs14@abdn.ac.uk

Marco Thiel
University of Aberdeen
Scotland
m.thiel@abdn.ac.uk

Claude Wischik
University of Aberdeen
c.m.wischik@abdn.ac.uk

Björn Schelter
Institute for Complex Systems and Mathematical Biology
University of Aberdeen, UK

b.schelter@abdn.ac.uk

PP2

Coherent Structures in Axially Symmetric Landau-Lifshitz-Gilbert-Slonczewski Equation

The Landau-Lifshitz-Gilbert-Slonczewski equation describes magnetization dynamics in a ferromagnetic thin film in the presence of an applied field and a spin polarized current. In the case of axial symmetry and with focus on one space dimension, we study the existence and stability of wavetrains, especially absolute and convective stability, and of domain wall-type coherent structures whose profiles asymptote to wavetrains or the constant up-/down-magnetizations. The coexistence and interaction of wavetrains and/or constant magnetization states is further evaluated. For certain polarization the Slonczewski term can be removed which allows for a more complete charaterization, including soliton-type solutions. Decisive for the solution structure is the polarization parameter as well as size of anisotropy compared with the difference of field intensity and current intensity normalized by the damping.

Lars Siemer
University of Bremen
Faculty Mathematics and Computer Science
lars.siemer@uni-bremen.de

Jens Rademacher
University of Bremen
Faculty of Mathematics and Computer Science
rademach@math.uni-bremen.de

Christof Melcher
RWTH Aachen University
melcher@rwth-aachen.de

PP2

System Parameter Variations from Attractor Deformation

In damage detection and sensing applications, repeated observations of system dynamics are often used to assess if system parameters are changing over longer periods of time. The process of determining parameter changes by examining dynamics is usually difficult for chaotic systems. Our research compares two methods for quantifying parameter changes in chaotic systems by analyzing Poincare sections. In the first method, every point on a given section is assigned an indexed bin and a histogram for each bin is constructed based on the surrounding density. Bins from different Poincare sections (corresponding to systems having different parameters) are matched by assigning a cost based on the differences between histograms. By comparing the locations of matched bins on their respective Poincare sections, an estimate of the parameter change can be made. In the second method, attractor comparison is realized by calculating the earth movers distance involved in moving points on one Poincare section to create another Poincare section. Location comparison again allows for an estimate of the parameter change to be made. Several variations of these two techniques are presented using data from simulated and physical systems. Particular attention is paid to the potential for detecting multiple parameter changes in the presence of noise.

Andrew R. Sloboda, Trung Tran
Bucknell University
ars027@bucknell.edu, tbt004@bucknell.edu

PP2

Bounds for Generalised Lyapunov Exponents for Random Products of Shears

We give lower and upper bounds on both the Lyapunov exponent and generalised Lyapunov exponents for the random product of positive and negative shear matrices. These types of random products arise in applications involving randomized stirring devices. The bounds, obtained by considering invariant cones in tangent space, give excellent accuracy compared to standard and general bounds, and are increasingly accurate with increasing shear. Bounds on generalised exponents are useful for testing numerical methods, since these exponents are difficult to compute.

Rob Sturman
University of Leeds
rsturman@maths.leeds.ac.uk

Jean-Luc Thiffeault
Dept. of Mathematics
University of Wisconsin - Madison
jeanluc@math.wisc.edu

PP2

Mean Field Reduction for Expanding Maps Coupled on Heterogeneous Networks

We consider expanding maps coupled on heterogeneous networks, meaning that each map is considered as sitting on one node of a graph and is perturbed by interactions with adjacent nodes. Loosely speaking, if $x_i(t)$ is the state of the i-th node at time t

$$x_i(t+1) = f_i(x_i(t)) + \sum_{j=1}^{n} A_{ij} h(x_i(t), x_j(t))$$

where f_i is the uncoupled dynamics, $h(x_i, x_j)$ is the interaction term between nodes i and j, and $A_{ij} \in \{0,1\}$ selects which interactions are present according to the edges of the network. We prove that under certain hypotheses for a large set of initial conditions, the dynamics of any highly connected node is given by

$$x_H(t+1) = \tilde{f}(x_H(t)) + \xi(t)$$

where $\tilde{f}$ is a map of the node's coordinate only that consider the mean interaction coming from the rest of the network, and $\xi(t)$ is a fluctuation term proven to remain small for a long time depending on the heterogeneity of the network. This reduction provides explanation for synchronisation and other type of behaviours.

Matteo Tanzi
Imperial College London
m.tanzi13@imperial.ac.uk

PP2

Bifurcation of Coherent Structures in Nonlocally Coupled System

Motivated by models for neural fields, we study the existence of pulses bifurcating from a spatially homogeneous state in nonlocally coupled systems of equations. More specifically, we look at equations of the form $U + K * U =$

$N(U;\mu)$, where N encodes nonlinear terms, K an even matrix convolution kernel. Assuming the presence of neutral modes, that is, solutions of the form $u \sim \exp(i\ell x)$ to the linear part, we show under appropriate assumptions on the nonlinearity and the unfolding in μ that pulses bifurcate. Such an analysis is carried out using center manifold reduction, when coupling is local, say, $K = \delta'$. Here, we rely on functional analytic methods using predictors from formal expansions and correctors obtained after preconditioning the nonlinear system.

Tianyu Tao
University of Minnesota
taoxx173@umn.edu

Arnd Scheel
University of Minnesota
School of Mathematics
scheel@math.umn.edu

PP2

A New Partitioned Method for Viscous Fsi

Fluid-structure interactions (FSI) are a common class of problems in several applications, including flow problems in biological and engineering applications. In this presentation we consider a particular class of FSI algorithms, *partitioned methods*, that loosely couple the fluid and structure solvers along a well defined interface. A common difficulty in partitioned FSI algorithms is the added mass instability: we demonstrate some new results which show how one can overcome the added mass instability with a careful choice of boundary conditions and discretization with the finite element method.

David Wells
Rensselaer Polytechnic Institute
wellsd2@rpi.edu

PP2

Connecting Vegetation Models with Data: the Role of Topography, on Multiple Scales, for Water Harvesting in Channeled Vegetation Patterns

In semi-arid climates, regions of self-organized striped patterned vegetation can arise. Soil water availability is thought to influence stripe properties such as spacing, width, and curvature. Here, focusing on channelized stripes, we compare local (catchment area) and non-local (upslope area) computational methods for estimating the effect of soil water presence on stripe characteristics. Satellite image and SRTM topography data from a number of channels found at sites in Somalia and Western Australia are used to test the approaches. The goal of this investigation is to help identify pattern properties from data that might provide good validity tests for the deterministic vegetation models.

Lucien D. Werner
Northwestern University
lucien.werner@gmail.com

Punit Gandhi
Mathematical Biosciences Institute, Ohio State University
gandhi.138@mbi.osu.edu

Karna V. Gowda
Northwestern University
karna.gowda@u.northwestern.edu

Sarah Iams
Harvard University
Cambridge, MA
siams@seas.harvard.edu

Mary Silber
University of Chicago
Dept. of Engineering Sciences and Applied Mathematics
msilber@galton.uchicago.edu

PP2

Goal-Oriented Network Design for Pairwise Comparison Ranking

Inferring the rankings of a set of objects such as documents or images is closely related to problems such as designing and optimization of search engines and recommendation systems. In many applications, direct ranking or scoring may be challenging and unreliable. Alternatively, pairwise comparisons are typically easier to obtain and more robust, especially for human decision makings. Consider a given collection of items with some unknown but intrinsic ordering, a Pairwise Comparison Network (PCN) is a directed network that encodes information about the pairwise comparison data/results, which can either be passively obtained or actively designed. In contrast to previous work which only considers single-shot experiments, we propose a two-round design of goal-oriented PCNs which allows for efficient additional data collection that yield much enhanced ranking inference. In particular, we present three such network designs using only partial observations of pairwise comparison data. Adopting the PageRank algorithm originally developed for search engines, we infer rankings from the designed PCNs and validated their effectiveness against alternative methods. In addition, we present analytical results for special types of PCNs and discuss potential extensions and challenges.

Shandeepa D. Wickramasinghe
Mathematics
Clarkson University
wickrabs@clarkson.edu

Christino Tamon
Clarkson University
ctamon@clarkson.edu

Jie Sun
Mathematics
Clarkson University
sunj@clarkson.edu

PP2

Spectra and Turing Instabilities for Reaction Diffusion Systems with Anomalous Diffusion

We consider activator-inhibitor systems with fractional diffusion, in particular subdiffusion, which renders the equation nonlocal in time. On the one hand, we consider the perturbation from regular to subdiffusion near Turing instabilities and show that spectra converge locally in the wavenumber, while in contrast to regular diffusion, large wavenumbers have slow decay. On the other hand, we study the change in nature of pattern forming instabilities when the anomalous diffusion exponents of activator and inhibitor is further from being regular. In addition to the Turing instability threshold, we find a threshold for large wavenumber instabilities. Finally, we discuss bifurcations

associated with marginally stable wavenumbers.

Jichen Yang
University of Bremen
Faculty of Mathematics and Computer Science
jyang@uni-bremen.de

Jens Rademacher
University of Bremen
jdmr@uni-bremen.de

PP2

Dynamics of a Class I Calcium Model

Oscillation in the concentration of free cytosolic calcium plays a crucial role in very many cell types, controlling processes such as cell growth, muscle contraction and gene expression. It is thus important that we understand the mechanisms underlying such oscillations. We have developed a simple mathematical model for certain types of calcium oscillations, and conjecture that the model is applicable to a variety of cell types; validity of the model has been confirmed by experimental data from three different cell types. We are thus interested in understanding the dynamics behind this model. This poster shows recent progress on understanding the role that the existence of multiple timescales has on determining the dynamics of the model.

Xueshan Yang, Vivien Kirk
University of Auckland
xyan900@aucklanduni.ac.nz, v.kirk@auckland.ac.nz

James Sneyd
University of Auckland
Department of Mathematics
sneyd@math.auckland.ac.nz

PP2

Political Elections and Third Parties: A Mathematical Model and Empirical Evidence

Despite a large portion of the US public thinking third political parties are necessary, third parties receive little representation in US politics. We formulate a differential equation system to model party positions and vote share in political elections, with focus on the role of third parties. Our model is different from many previous models in our key hypothesis — voters "satisfice": they accept a party that is good enough and do not obsess over other options. This is motivated by psychological research on decision making, especially with incomplete information. Our model has two major implications. First, for a 2-party system, the possibility of additional parties can significant change its behavior. Second, having less parties, or higher barriers for minor parties, can lead to more extremist vote distributions in elections. We use empirical data of party positions in the US and worldwide to validate our model, and find strong support.

Vicky Chuqiao Yang, Daniel M. Abrams
Northwestern University
vcy@u.northwestern.edu, dmabrams@northwestern.edu

Georgia Kernell
University of California, Los Angeles
gkernell@ucla.edu

Adilson E. Motter
Northwestern University
motter@northwestern.edu

PP2

Stability Properties of Flying Snakes During Transient Glides

Flying snakes of the genus *Chrysopelea* turn their body into a morphing wing and perform controlled aerial glides using three-dimensional undulation. Here, we investigate the stability properties of snake gliding flight using reduced-order modeling, phase space analysis, and by measuring body undulation waveforms in glide trajectories originating from 8.5 m. The empirical waveforms are then used as input to a dynamic model of snake flight to investigate the coupling of aerodynamic and inertial moments on flight stability as the simulated glider progresses through the horizontal-vertical velocity space. We find that inertial moments dominate about the yaw axis, a feature that could be exploited for maneuvering, and which also may be useful as a control modality for bioinspired engineered gliders.

Isaac Yeaton
Virginia Tech
iyeaton@vt.edu

Gary K. Nave
Virginia Tech
Department of Biomedical Engineering and Mechanics
gknave@vt.edu

John Socha
Virginia Tech
jjsocha@vt.edu

Shane D. Ross
Virginia Tech
Engineering Mechanics program
sdross@vt.edu

PP2

Pattern Formation in Marsh Ecosystems Modeled Through the Interaction of Marsh Vegetation, Mussels and Sediment

Spatial patterning in multi-species communities can be critical to ensuring their proper function and survival, making the investigation of self-organization in ecology crucial for understanding the underlying interactions in various ecosystem communities and their ability to adapt to emerging environmental changes. In this presentation, we focus on finger-like projections consisting of marsh vegetation, mussels and accumulated sediment observed on the marsh shorelines of the York River. Although we consider this specific location, similar structures may exist in other marsh communities. We propose a system of reaction-diffusion equations with nonlocal interactions to model the formation of these aggregations through interactions between marsh vegetation, mussels and sediment. The model presents a phenomenological approach, focused on the self-organization as a result of interactions between species. We analytically and numerically study the three-species system (marsh vegetation-mussels-sediment), as well as the mussel-free subsystem, to gain understanding into the possible dynamics. In addition, snapshots of the system are analyzed along an erosion gradient to investigate the system's transition to a degraded state with increasing environmental stresses.

Sofya Zaytseva
The College of William and Mary
szaytseva@email.wm.edu

Leah Shaw
College of William and Mary
lbshaw@wm.edu

Junping Shi
College of William and Mary
Department of Mathematics
shij@math.wm.edu

Rom Lipcius
Virginia Institute of Marina Science
rom@vims.edu

PP2

A Parameter Estimation Method Using Linear Response Statistics

This paper presents a new parameter estimation method for Ito diffusion such that the resulting model predict the equilibrium statistics as well as the sensitivities of the underlying system under external disturbances. Our formulation does not require the knowledge of the underlying system, however we assume that the linear response statistics can be computed via the fluctuation-dissipation theory. The main idea is to fit the model to a finite set of "essential" statistics that is sufficient to approximate the linear response operators. In a series of test problems, including a simplified turbulence model and a Langevin dynamics model, we will show the consistency of the proposed method in the sense that if we use the proposed method to estimate the parameters of the underlying model, then we must obtain the true parameters.

He Zhang
Department of Mathematics
The Pennsylvania State University
hqz5159@psu.edu

John Harlim
Pennsylvania State University
jharlim@psu.edu

Xiantao Li
Department of Mathematics
Pennsylvania State University
xli@math.psu.edu

PP2

Geometry of Transition Dynamics for a Buckled Beam

We present a dynamic buckling model for a moderately buckled beam. The analytical model is established by the Euler-Bernoulli beam model with a two-mode truncation. Using the Legendre transformation, the two-mode Hamiltonian, which is the sum of a kinetic energy term and a potential energy term is obtained from the Lagrangian. The form of the potential energy—two stable wells connected by rank-1 saddle points—shows an analogy with resonance transitions in celestial mechanics or molecular reconfigurations in chemistry, where here transition corresponds to switching between two stable beam configurations. Then, from the Hamilton's equations, the analytical equilibria are determined and linearization of the equations of motion about the saddle is obtained. After computing the eigenvalues and eigenvectors of the coefficient matrix associated with the linearization, the symplectic transformation is given which puts the Hamiltonian into normal form and simplifies the equations, allowing us to use the conceptual framework known as tube dynamics. The flow in the equilibrium region of phase space as well as the invariant manifold tubes in position space are discussed. Also, we account for the addition of damping in the tube dynamics framework, which leads to a richer set of behaviors in transition dynamics than previously explored.

Jun Zhong
Dept. of Biomedical Engineering & Mechanics, Virginia Tech
junzhong@vt.edu

L. N. Virgin
Dept. of Mechanical Engineering, Duke University
l.virgin@duke.edu

Shane D. Ross
Virginia Tech
Engineering Mechanics program
sdross@vt.edu