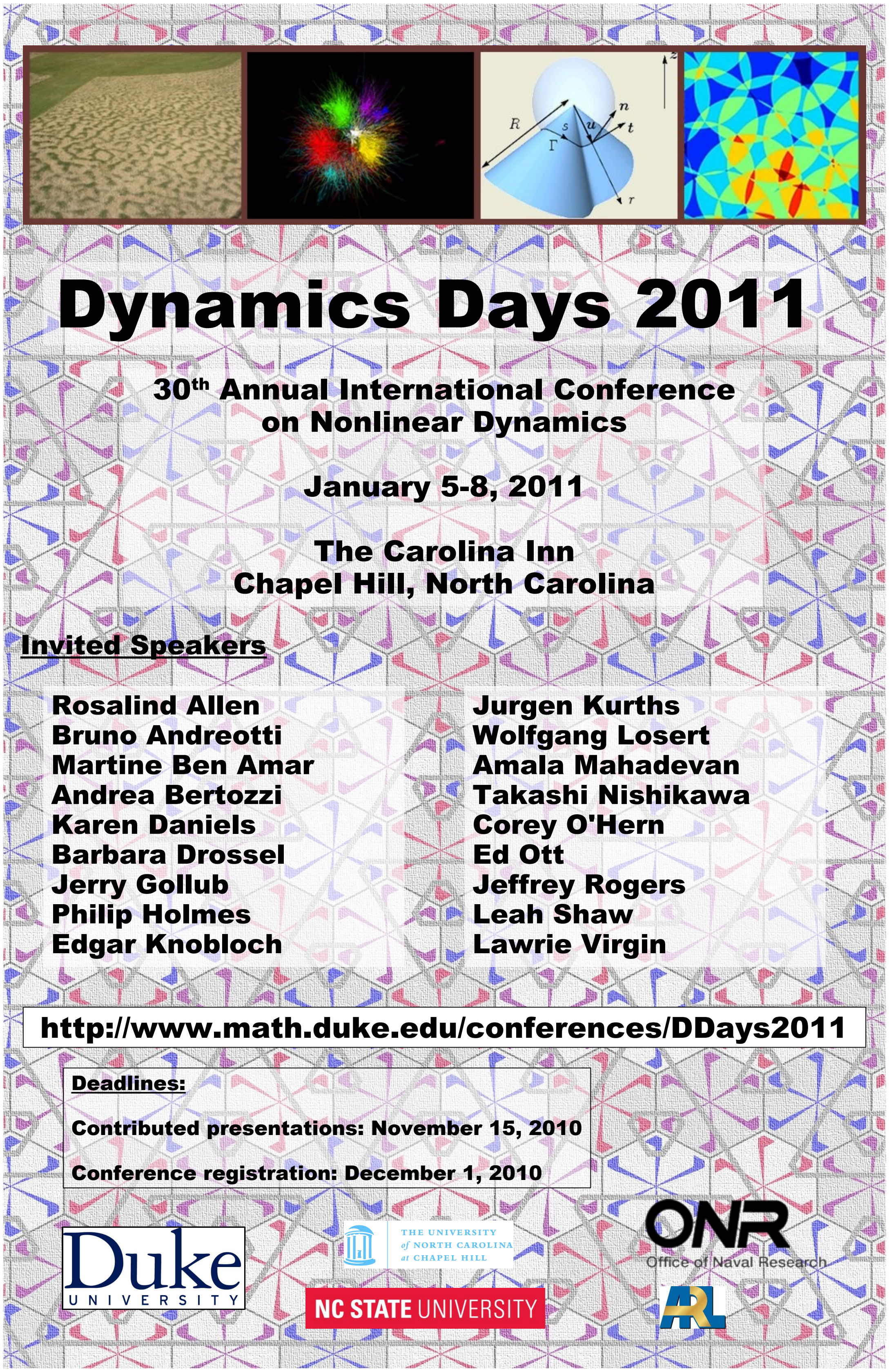
Abstracts Submitted for Talks and Posters
(final version)



Schedule

Wednesday, January 5, 2011[1]

8:45 Opening Remarks

9:00 – 10:40 **Session 1**, Chair: Joshua Socolar, Duke University

- 9:00 **I3** – Statistical Mechanics of Packing: From Proteins to Cells to Grains
  Corey O'Hern, Yale University
- 9:40 **I2** – Spatially localized structures in two dimensions
  Edgar Knobloch, University of California, Berkeley
- 10:20 **C1** – An Elementary Model of Torus Canards
  Anna Barry, Boston University

10:40 Break

11:00 – 12:40 **Session 2**, Chair: Thomas Witelski, Duke University

- 11:00 **I6** – The Path to Fracture: Dynamics of Broken Link Networks in Granular Flows
  Wolfgang Losert, University of Maryland
- 11:40 **C2** – Flexibility Increases Energy Efficiency of Digging in Granular Substrates
  Dawn Wendell, MIT
- 12:00 **I4** – Ripples, dunes, bars and meanders
  Bruno Andreotti, ESPCI

12:40 Lunch

2:00 – 4:00 **Session 3**, Chair: Joshua Socolar, Duke University

- 2:00 **I5** – The Nonlinear Population Dynamics of Pacific Salmon
  Barbara Drossel, University of Darmstadt
- 2:40 **I8** – Erosional Channelization in Porous Media
  Amala Mahadevan, Boston University
- 3:20 **C3** – Determining the onset of chaos in large Boolean networks
  Andrew Pomerance, University of Maryland
- 3:40 **C4** – Exploring mesoscopic network structure with communities of links
  James Bagrow, Northeastern University

4:00 Break

4:20 – 5:20 **Session 4**, Chair: Thomas Witelski, Duke University

- 4:20 **I7** – Swarming by Nature and by Design
  Andrea Bertozzi, UCLA
- 5:00 **C5** – Sub-wavelength position-sensing using a wave- chaotic cavity with nonlinear feedback
  Hugo Cavalcante, Duke University

5:20 Break for Dinner

[1] General Guidelines: Invited presentations are 40 minutes total (35 minutes presentation, 5 minutes questions), Contributed presentations are 20 minutes total (16 minutes presentation, 4 minutes questions), space for poster presentations is limited to a maximum size of 4 feet by 4 feet for each poster.

Thursday, January 6, 2011

9:00 – 9:40 **Session 5**, Chair: Robert Behringer, Duke University

- 9:00 **I1** – Still Running! Recent Work on the Neuromechanics of Insect Locomotion
  Phillip Holmes, Princeton University
- 9:40 **C6** – Fluid rope tricks
  Stephen Morris, University of Toronto
- 10:00 **C7** – Three-dimensional structure of a sheet crumpled into a sphere
  Anne Dominique Cambou, University of Massachusetts, Amherst

10:20 Break

10:40 – 12:00 **Session 6**, Chair: Edward Ott, University of Maryland

- 10:40 **I9** – Evolutionary Dynamics for Migrating Populations
  Rosalind Allen, University of Edinburgh
- 11:20 **C8** – Predicting criticality and dynamic range in complex networks: effects of topology
  Daniel Larremore, University of Colorado at Boulder
- 11:40 **C10** – Creating Morphable Logic Gates using Logical Stochastic Resonance in an Engineered Gene Regulatory Network
  Anna Dari, Arizona State University

12:00 Lunch

2:00 - 3:40 **Session 7**, Chair: Brian Utter, James Madison University

- 2:00 **I10** – Stochastic Extinction along an Optimal Path
  Leah Shaw, College of William and Mary
- 2:40 **C9** – Chaos Elimination of Fluctuations in Quantum Tunneling Rates
  Louis Pecora, Naval Research Laboratory
- 3:00 **I14** – Dynamics and Interactions of Swimming Cells
  Jerry Gollub, Haverford College

3:40 – 7:30 Break for afternoon and dinner

7:30 – 8:10 **Session 8**, Chair: Karen Daniels, NCSU

- 7:30 **I12** – Low Dimensional Dynamics in Large Systems of Coupled Oscillators
  Edward Ott, University of Maryland

8:15 –10:00 **Poster Session 1 - Setup and Desserts**

Friday, January 7, 2011

9:00 – 10:20 **Session 9**, Chair: Joshua Socolar, Duke University

9:00 **I13** – Nonlinear programs and DARPA
Jeffrey Rogers, DARPA

9:40 **C11** – Measuring Information Flow in Anticipatory Systems
Shawn Pethel, U.S. Army RDECOM

10:00 **C12** – Time delays in the synchronization of chaotic coupled systems with feedback
José Rios Leite, Universidade Federal de Pernambuco

10:20 Break

10:40 – 12:20 **Session 10**, Chair: Thomas Witelski, Duke University

10:40 **I11** – Compensatory structures in network synchronization
Takashi Nishikawa, Clarkson University

11:20 **C13** – Folding: the nonlinear step in fluid mixing
Douglas Kelley, Yale University

11:40 **C14** – Trapping of Swimming Particles in Chaotic Fluid Flow
Nicholas Ouellette, Yale University

12:00 Lunch

2:00 – 4:00 **Session 11**, Chair: Joshua Socolar, Duke University

2:00 **I15** – Network of Networks and the Climate System
Jurgen Kurths, University of Potsdam

2:40 **C15** – What is the front velocity in wave propagation without fronts? Epidemics on complex networks provide an answer
Dirk Brockmann, Northwestern University

3:00 **I16** – Shape instability of growing tumors
Martine Ben Amar, University of Paris

3:40 **C16** – Reconstruction of Cardiac Action Potential Dynamics using Computer Modeling with Feedback from Experimental Data
Laura Munoz, Cornell University

4:00 – 6:00 **Poster Session 2**

6:00 Break for dinner

Saturday, January 8, 2011

9:30 – 10:30 **Session 12**, Chair: Robert Behringer, Duke University

- 9:30 **I17** – Faults & Earthquakes as Granular Phenomena: Controls on Stick-Slip Dynamics
  Karen Daniels, North Carolina State University
- 10:10 **C17** – Effects of Shape on Diffusion
  Rob Shaw, Santa Fe Complex

10:30 Break

10:50 – 11:50 **Session 13**, Chair: Michael Shearer, NCSU

- 10:50 **C18** – Crowd behavior: Synchronization of multistable chaotic systems by a common external force
  Alexander Pisarchik, Centro de Investigaciones en Optica
- 11:10 **I18** – Rocking and Rolling
  Lawrie Virgin, Duke Univ. Engineering

11:50 **End of Conference. Have a safe trip home!**

Invited Talks

- **Models for bacterial population dynamics and evolution**
  Rosalind Allen, *University of Edinburgh*
- **Ripples, dunes, bars and meanders**
  Bruno Andreotti, *ESPCI*
- **Swarming by Nature and by Design**
  Andrea Bertozzi, *UCLA*
  The cohesive movement of a biological population is a commonly observed natural phenomenon. With the advent of platforms of unmanned vehicles, such phenomena has attracted a renewed interest from the engineering community. This talk will cover a survey of the speaker's research and related work in this area ranging from aggregation models in nonlinear PDE to control algorithms and robotic testbed experiments. We conclude with a discussion of some interesting problems for the applied mathematics community.
- **Shape instability of growing tumors**
  Martine Ben Amar, *University of Paris*
- **Faults & Earthquakes as Granular Phenomena: Controls on Stick-Slip Dynamics**
  Karen Daniels, *North Carolina State University*
  Granular and continuous materials fail in fundamentally different ways, yet inherently discontinuous natural fault materials have often been modeled as continuum processes. A long-standing question is whether the granular nature of fault material such as gouge plays a major role in controlling seismicity and periodicity in geological faults. In both natural faults and granular experiments, the ability of the material to rearrange in response to strain is an important effect on its effective strength. I will describe laboratory experiments on a photoelastic granular aggregate which allow us to investigate these particle-scale controls on bulk behaviors. By adjusting the pressure and/or volume of the system, we are able to control both the size-distribution of stick-slip events (either power-law or exponential) and their periodicity/aperiodicity. In addition, we find scaling relations connecting the size and duration of individual events which permit comparison with mean-field models of failure.
- **The Nonlinear Population Dynamics of Pacific Salmon**
  Barbara Drossel, *University of Darmstadt*
- **The Path to Fracture: Dynamics of Broken Link Networks in Granular Flows**
  Wolfgang Losert, *University of Maryland*
- **Dynamics and Interactions of Swimming Cells**
  Jerry Gollub, *Haverford University*
- **Still Running! Recent Work on the Neuromechanics of Insect Locomotion**
  Philip Holmes, *Princeton University*
  I will describe several models for running insects, from an energy-conserving biped with passively-sprung legs to a muscle-actuated hexapod driven by a neural central pattern generator (CPG). Phase reduction and averaging theory collapses some 300 differential equations that describe this neuromechanical model to 24 one-dimensional oscillators that track motoneuron phases. The reduced model accurately captures the dynamics of unperturbed gaits and the effects of impulsive perturbations, and phase response and coupling functions provide improved understanding of reflexive feedback mechanisms. Specifically, piecewise-holonomic constraints due to intermittent foot contacts confers asymptotic stability on the CPG- driven feedforward system, the natural dynamics features a slow subspace that permits maneuverability, and leg force sensors modulate firing patterns to mitigate large perturbations. More generally, I will argue that both simple models and large simulations are necessary to understand such complex systems. The talk will draw on joint work with Einat Fuchs, Robert Full, Raffaele Ghigliazza, Raghu Kukillaya, Josh Proctor, John Schmitt, Justin Seipel and Manoj Srinivasan. Research supported by NSF and the J. Insley Blair Pyne Fund of Princeton University.
- **Spatially localized structures in two dimensions**
  Edgar Knobloch, *UC Berkeley*

Many continuum systems in physics exhibit a spatially localized response to spatially homogeneous forcing. The resulting structures are frequently called dissipative solitons. In this talk I will describe the phenomenon of homoclinic snaking that is responsible for the presence of these states, together with the associated snakes-and-ladders structure of the snaking region, i.e. the parameter region containing such localized structures. I will describe this behavior in both one and two spatial dimensions, focusing on the growth of the structures as one follows branches of localized structures from small to large amplitude. I will illustrate the results using both model equations such as the Swift-Hohenberg equation and "real" systems such as binary fluid convection.

- **Network of Networks and the Climate System**
  Jurgen Kurths, *University of Potsdam*
  We introduce a novel graph-theoretical framework for studying the interaction structure between sub-networks embedded within a complex network of networks. This allows us to quantify the structural role of single vertices or whole sub-networks with respect to the interaction of a pair of subnetworks on local, mesoscopic, and global topological scales. Climate networks have recently been shown to be a powerful tool for the analysis of climatological data. Here we use the concept of network of networks by introducing climate subnetworks representing different heights in the atmosphere. Parameters of this network of networks, as cross-betweenness, uncover relations to global circulation patterns in oceans and atmosphere. The global scale view on climate networks offers promising new perspectives for detecting dynamical structures based on nonlinear physical processes in the climate system.
- **Erosional Channelization in Porous Media**
  Amala Mahadevan, *Boston University*
  We explore the evolution of erosional channels induced by fluid flow in a granular porous medium. When the fluid-induced stresses exceed a critical threshold, grains are dislodged and transported with the flow, thereby altering the porosity of the medium. This in turn affects the local hydraulic conductivity and pressure in the medium and results in the growth and development of channels that preferentially conduct the flow. We propose a continuum multiphase model that captures the formation of erosional channels by coupling the spatiotemporal evolution of the granular and liquid phases to the dynamical properties of the fluid and porous substrate.
- **Compensatory structures in network synchronization**
  Takashi Nishikawa, *Clarkson University*
  Synchronization, in which individual dynamical units keep in pace with each other in a decentralized fashion, depends both on the dynamical units and on the properties of the interaction network. Yet, the role played by the network has resisted comprehensive characterization within the prevailing paradigm that interactions facilitating pair-wise synchronization also facilitate collective synchronization. Here we challenge this paradigm and show that networks with best complete synchronization, least coupling cost, and maximum dynamical robustness, have arbitrary complexity but quantized total interaction strength, which constrains the allowed number of connections. It stems from this characterization that negative interactions as well as link removals can be used to systematically improve and optimize synchronization properties in both directed and undirected networks. For networks of nonidentical maps, we show that these compensatory modifications to the network structure can lead to complete synchronization, despite the heterogeneity of the dynamical units. These results extend the recently discovered compensatory perturbations in metabolic networks to the realm of oscillator networks and demonstrate why "less can be more" in network synchronization.
- **Statistical Mechanics of Packing: From Proteins to Cells to Grains**
  Corey O'Hern, *Yale University*
  Over the past ten years, my research group has focused on understanding the statistical mechanics of jammed particulate systems such as colloidal glasses and granular materials. Using a variety of computational and theoretical techniques, we have found many fascinating results for nonequilibrium systems that do not occur in thermal liquids and solids. Examples include the breakdown of equi-probability of microstates as in the microcanonical ensemble and strongly nonharmonic response of granular solids even for vanishingly small vibrations. In addition, we have shown that geometric and packing constraints often determine the key structural, mechanical, and even dynamical properties of jammed systems. More recently, my research group has been investigating to what extent packing constraints play a role in determining biological structures and interactions. I will highlight our studies

of the conformational dynamics of intrinsically disordered proteins, the binding affinity of repeat proteins and their cognate peptides, and the size, shape, and mobility of epithelial cells in monolayers.

- **Low Dimensional Dynamics in Large Systems of Coupled Oscillators**
  Edward Ott, *University of Maryland*
  The issue of determining the emergent collective behavior of these systems is of great practical and basic concern. Examples include chirping crickets, pedestrian induced shaking of footbridges, control of circadian rythm by the superchiasmatic nucleus, pacemaker cells in the heart, chemical oscillators, birdsong, coupled lasers, Josephson junction circuits, bubbly fluids, neuronal oscillations in the brain and many others. A convenient characterization of the individual oscillators is the phase oscillator description where the state of each oscillator is given solely by a single phase variable. The simplest example is the Kuramoto model. In the past, models of this type have been investigated primarily via direct numerical computation for the time evolution of all the many coupled equations describing the system. In this talk I will describe an exact analytical technique [1] that reduces the study of the emergent collective macroscopic behavior of these systems to the solution of just a few ordinary differential equations. In particular, it is found that all initial conditions are attracted to an invariant manifold in the state space [2], and evalution on this manifold is governed by a low dimensional dynamical system. The technique is widely applicable, and I will indicate some examples where it has already been employed to uncover the attractors and bifurcations of large oscillator systems.
  [1] E.Ott and T.M.Antonsen, Chaos (2008).
  [2] E.Ott and T.M.Antonsen, Chaos (2009).

- **Nonlinear Programs and DARPA**
  Jeffrey Rogers, *DARPA*

- **Stochastic Extinction along an Optimal Path**
  Leah Shaw, *College of William and Mary*
  Extinction of an epidemic or a species is a rare event that occurs due to a large, rare stochastic fluctuation. The extinction process follows an optimal path that maximizes the probability of extinction. We show that the optimal path is maximally sensitive to initial conditions and thus can be detected using finite-time Lyapunov exponents. Several stochastic population models are presented, and the extinction process is examined in a dynamical systems framework.

- **Rocking and Rolling**
  Lawrie Virgin, *Duke Univ. Engineering*
  A system at rest is subject to the sudden application of (harmonic) forcing. The resulting transient dynamic response may typically lead to various kinds of periodic behavior or chaos. However, if an underlying potential energy well in which the system lives is limited in extent, then the system may exit the local vicinity of the initial equilibrium, and perhaps go off to infinity. This talk will focus on two types of mechanical system in which we seek to characterize the likelihood of an extreme outcome: a ball that rolls on a curved surface, and a rectangular block that rocks on a table. These systems are relatively easy to model, and easy to build experimentally, but their behavior is often highly erratic and unpredictable.

Contributed Talks

Exploring mesoscopic network structure with communities of links, James Bagrow, *Northeastern University*

Complex networks have recently received much attention as a productive way to study diverse phenomena ranging from biological interactions in the cell to societal-wide activities in human dynamics. One important problem is the identification of Communities, mesoscopic-scale groups of densely connected nodes. These groups may correspond to functionally related proteins, or to the social circles that people move through in their daily lives. Finding communities is usually considered a partitioning problem, where each node is placed into exactly one community. Yet nodes often fulfill multiple structural and functional roles in the network, meaning that communities overlap and nodes belong to multiple communities. We show that it is still possible to study overlapping structure with a partition, by forming groups of links rather than nodes. This has distinct advantages and achieves accurate results according to empirical measures. We also describe how some basic assumptions about communities may not always hold, with important dynamical and functional consequences.

An Elementary Model of Torus Canards, Anna Barry, *Boston University*

We study the recently-discovered phenomena of torus canards. These are a higher-dimensional generalization of the classical canard orbits familiar from planar systems, and arise in fast-slow systems of ordinary differential equations in which the fast subsystem contains a saddle-node bifurcation of periodic orbits. Torus canards spend long times near slowly-varying families of attracting periodic orbits and then near slowly-varying families of repelling periodic orbits, in alternation. We carry out a detailed study of torus canards in an elementary third-order system that consists of a rotated van der Pol equation in which the rotational symmetry is broken by including a phase-dependent term in the slow component of the vector field. In the regime of fast rotation, the torus canards behave much like their planar counterparts. In the regime of slow rotation, the phase dependence creates rich torus canard dynamics. Similar dynamics have been observed in a mathematical model of action potential generation in Purkinje cells. Stable torus canard solutions exist for open sets of parameter values, correspond to amplitude-modulated spiking of the neural dynamics, and arise exactly in the transition region between rapid spiking and bursting in this model.

What is the front velocity in wave propagation without fronts? - Epidemics on complex networks provide an answer, Dirk Brockmann, *Northwestern University*

The spatiotemporal patterns of infectious diseases that spread nowadays typically lack a well defined wave front as human mobility is multi-scale. The structure of emergent patterns is difficult to assess quantitatively, in particular spreading speeds are difficult to define and compare in different scenarios. We present a novel way to look at contagion phenomena on complex networks using the underlying topological structure of the network. Shortest-path distances and arrival times are used to redefine the velocity of spreading patterns. We extend the idea of a wavefront that can be directly observed in simple networks like a regular lattice to the class of complex networks which in traditional views exhibit complicated patterns. This method substantially simplifies the way dynamics are analyzed and explains why patterns in complex modeling approaches share many similarities. Disease dynamics on various complex networks ranging from artificial to real human mobility networks show the benefit of representing the spatio-temporal patterns based on topological features of the network.

Sub-wavelength position-sensing using a wave-chaotic cavity with nonlinear feedback, Hugo Cavalcante, *Duke University*

Hugo L. D. de Souza Cavalcante, Seth D. Cohen, Daniel J. Gauthier, Department of Physics, Duke University, Durham, NC, USA

We develop a new dynamical system that consists of a nonlinear element whose output is passed through a wave-chaotic cavity and then fed back to the nonlinear element. The nonlinearity of the system is provided by a transistor-based circuit. The circuit's input and output voltage couple to the radiation inside the cavity through broadband antennas, and the multipath reflections of the signal inside the cavity constitute multiple delayed-feedback loops. The path lengths and coupling strengths of these feedback delays depend sensitively on the position of a sub-wavelength scatterer placed into the cavity. The primary purpose of this work is to show that quantities observable in the dynamics, such as bifurcations points or frequencies of oscillation, are linearly proportional to the position of this scatterer object. Fixing the position of this scatterer, we generate a bifurcation in the system's dynamics by scanning the bias voltage of the nonlinear circuit. We find that the bifurcation point is sensitive to displacements of the scatterer position as small as 10 micrometers (see poster by Seth D. Cohen *et al.*). Because of fluctuations on system's parameters this method allows for one-dimensional position-tracking with resolution of 60 micrometers. This last number is 2,500 times smaller than the minimum wavelength of radiation inside the cavity (15 cm). Alternatively, we can measure the frequency of a periodic oscillation as a function of the object position. We have found that the frequency also changes continuously and allows similar tracking of the scatterer position. These techniques may find potential applications in radio-based sub-wavelength imaging and sensors with through-wall capabilities. We gratefully acknowledge the support of the ONR MURI "Exploiting Nonlinear Dynamics for Novel Sensor Networks".

Three-dimensional structure of a sheet crumpled into a sphere, Anne Dominique Cambou, *University of Massachusetts, Amherst*

We probe the interior of thin aluminum sheets hand-crumpled into three-dimensional balls to characterize the resulting structure that has low volume fraction but high resistance to further compression. We use X-ray computerized microtomography to determine the location of the sheet in the volume. From a reconstruction of the X-ray images, we perform fully three-dimensional analyses of their curvature, orientation, and local stacking. In order to identify possible anisotropy and inhomogeneity imposed by the method of crumpling, we present an analysis of the radial dependence of these metrics of the geometry. Our results reveal that the internal three-dimensional geometry of a crumpled ball is in many respects isotropic and homogeneous. However, we find inhomogeneously distributed local nematic ordering by the layering of the folded sheet into parallel stacks. We also present ongoing work on the dynamics of the crumpling process.

Creating Morphable Logic Gates using Logical Stochastic Resonance in an Engineered Gene Regulatory Network, Anna Dari, *Arizona State University*

The idea of Logical Stochastic Resonance (LSR) is adapted and applied to an gene regulatory network (GRN) in the bacteriophage λ. The resultant computing device is able to work as an AND or OR gate interchangeably in the presence of noise. Noise is critical for the existence and operation of the gates. We have computed the gate "performance" as a function of noise intensity and shown that the biological system output is the logical combination of the two data inputs for a range of noise intensities, and the GRN phage λ can switch from the AND to OR gate as desired; this switching can be accomplished, for a fixed external noise level, by adjusting other deterministic system parameters. LSR on a GRN, that has the capability of being reconfigured, could be combined, in near future, with other logic modules (done by different sets of input/output signals) to increase the computational power and functionality of an engineered GRN. Such networks may allow predictable and robust control in fluctuating cellular environments and thereby have a significant impact in the design of synthetic biological systems such as recently created bacterial cells controlled by chemically synthesized genomes.

Folding: the nonlinear step in fluid mixing, Douglas Kelley, *Yale University*

Efficient large-scale mixing of an impurity in a fluid depends on stretching and folding–together they expand the periphery of material volumes, allowing molecular diffusion to mix efficiently. The linear step in this process, stretching, has been studied extensively with tools like finite-time Lyapunov exponents. But folding, corresponding to nonlinear deformation of materials volumes, has been more difficult to study. We use nonlinearity of the folding transformation to separate it from stretching and study both steps independently. Our data come from a quasi-two-dimensional laboratory flow in which we measure the velocity of roughly 30,000 Lagrangian particles per frame. At short deformation times, linear stretching dominates, but once fluid elements have elongated, nonlinear folding becomes rapidly stronger and begins to dominate the deformation. The relative strength of the two processes also varies strongly in space. Our analysis takes a first step beyond the analysis of nonlinear mixing with purely linearized measures. This work is supported by the National Science Foundation.

Predicting criticality and dynamic range in complex networks: effects of topology, Daniel

Larremore, *University of Colorado at Boulder*
We study the effect of network structure on the dynamical response of networks of coupled discrete-state excitable elements which are stochastically stimulated by an external source. Such systems have been used as toy models for the dynamics of some human sensory neuronal networks and neuron cultures. The collective dynamics of such systems depends on the topology of the connections in the network. Here we develop a general theoretical approach to study the effects of network topology on dynamic range, which quantifies the range of stimulus intensities resulting in distinguishable network responses. We find that the largest eigenvalue of the weighted network adjacency matrix governs the network dynamic range. Specifically, a largest eigenvalue equal to one corresponds to a critical regime with maximum dynamic range. This result appears to hold for random, all-to-all, and scale free topologies, and is robust to the inclusion of time delays and refractory states. We gain deeper insight on the effects of network topology using a nonlinear analysis in terms of additional spectral properties of the adjacency matrix. We find that homogeneous networks can reach a higher dynamic range than those with heterogeneous topology. Our analysis, confirmed by numerical simulations, generalizes previous studies in terms of the largest eigenvalue of the adjacency matrix. These results provide a better understanding of the sources of enhanced dynamic range of neuronal networks and may be applicable to the study of other systems that can be modeled as a network of coupled excitable elements (e.g., epidemic propagation).

Fluid rope tricks, Stephen Morris, *University of Toronto*
A thread of viscous fluid, like honey, falling onto a surface undergoes a buckling instability known as the "rope coiling effect". The thread spontaneously wraps itself into helical loops before the fluid settles onto the surface. We will discuss a generalization of this classic problem, known as the "fluid mechanical sewing machine", in which the surface is replaced by a moving belt. The belt breaks the rotational symmetry of the rope coiling, leading to an astonishing zoo of states as a function of the belt speed and nozzle height. We constructed a precision apparatus that can systematically explore this zoo and identify the modal structure of, and bifurcations between, the various "stitch patterns".

Reconstruction of Cardiac Action Potential Dynamics using Computer Modeling with Feedback from Experimental Data, Laura Munoz, *Cornell University*
Sudden cardiac arrest is a leading cause of death in the industrialized world. Most cases of sudden cardiac arrest are due to ventricular fibrillation (VF), a lethal heart arrhythmia. Closed-loop observer design techniques are relevant to the study of arrhythmias, since such methods could be used to improve the performance of anti-arrhythmic electrical stimulus protocols, or to provide enhanced information to researchers who investigate arrhythmias during in vitro or in vivo experiments. In this study, an observer has been developed based on a mathematical model of cardiac action potential (AP) dynamics, in order to reconstruct unmeasured quantities, such as AP durations (APDs) at locations away from sensing electrodes. Tools for observer analysis and design were applied to a two-variable Karma model of AP dynamics, and it was confirmed that cellular membrane potential data could be used to reconstruct the state of a single-cell system, and that Luenberger feedback could stabilize the observer for a multi-cell system. Next an observer with 1D spatial geometry was tested with microelectrode membrane potential data from a 2.1cm in vitro canine Purkinje fiber. It was shown that the observer produced more accurate APD estimates than the model by itself. The ability of feedback to stabilize the observer about different categories of AP patterns in multi-cell systems will be discussed.

Trapping of Swimming Particles in Chaotic Fluid Flow, Nicholas Ouellette, *Yale University*
Small motile particles in fluid environments are well known to show a wide variety of complex behaviors, ranging from pattern formation to the driving of macroscopic flow. Less is known, however, about the dynamics of swimming particles in flows that are a priori nontrivial and chaotic. Using a simple computational model, we study the behavior of pointlike, spherical particles that have their own intrinsic velocity and are advected by a two-dimensional chaotic flow field. We show that small but finite values of the intrinsic swimming speed can sometimes lead to weaker particle transport, as swimmers can become stuck for long times in traps that form near the elliptic islands of the underlying flow field.

Chaos Elimination of Fluctuations in Quantum Tunneling Rates, Louis Pecora, *Naval Research Laboratory*

We study quantum tunneling in various shaped, two-dimensional, flat, double wells by calculating the energy splitting between symmetric and antisymmetric state pairs. For shapes that have regular or nearly regular classical behavior (e.g. rectangular or circular wells) we find that tunneling rates for nearby energy states vary over wide ranges. Rates for energetically close quantum states can differ by several orders of magnitude. As we transition to well shapes that admit more classically chaotic behavior the range of tunneling rates narrows, often by an order of magnitude or more. For well shapes in which the classical behavior appears to be fully chaotic the tunneling rates' range narrows to about a factor of 3 or so between the smallest and largest rates in a wide range of energies. This dramatic narrowing appears to come from destabilization of periodic orbits in the regular wells that produce the largest and smallest tunneling rates which eliminates large fluctuations. We have developed a theory based on a random plane wave approximation which quantitatively reproduces the changes in tunneling rate distributions seen in the numerical results and explains their statistics.

Measuring Information Flow in Anticipatory Systems, Shawn Pethel, *U.S. Army RDECOM*

We report that the apparent direction of information flow in an anticipatory (predictive) network depends on measurement resolution. Transfer entropy estimates from low resolution data show net information flow away from an anticipatory element while high resolution measurements show the flow towards it. At low resolutions anticipatory elements will appear to be driving the network dynamics even when there is no possibility of such an influence. Because coarse graining is generally required for the estimation of transfer entropy this effect is likely to be encountered. We present numerical results for coupled maps and analytical results for a Markov chain model and discuss a feature that can be used to detect the presence of anticipatory dynamics.

Crowd behavior: Synchronization of multistable chaotic systems by a common external force, Alexander Pisarchik, *Centro de Investigaciones en Óptica*

It was noted long time ago that individuals being in a crowd lose their personality and act synchronously as a common system. While psychologists and sociologists give different explanations for this phenomenon, an alternative approach is to consider individuals as dynamical systems, and say that they are affected by the same external force if they are looking at or listening to the same object (a leader, a government, a football game, a rock concert, a movie, etc.). When the individuals think alike, so that collective or crowd behavior can be expected, we may say they are synchronized. In sociology, synchronization phenomena are very relevant to better understand the mechanisms underlying the formation of social collective behaviors, such as the sudden emergence of new ideas, habits, fashions or leading opinions. To find out what kind of state might be associated with people's opinions and emotions, we first need an answer to: What kind of motion can be related to the brain functioning? Numerous experiments with neuronal activity and electroencephalograms (EEG) indicate that their dynamics exhibit many characteristics inherent to chaos; this means that the overall system which gives rise to the EEG potentials, namely the brain, is in a chaotic state. Moreover, many researchers have confirmed that multistability is inherent to neuronal behavior and manifests itself in many brain functions, such as audio and visual perception, and is even responsible for memory. An external force, generally chaotic or stochastic provokes jumps between coexisting attractors and create a new synchronization state. We study this synchronization problem with prototype bistable chaotic Rössler oscillators subject to a common chaotic or noisy force. Depending on the coupling strength, different synchronization states are distinguished and analyzed for both cases.

Determining the onset of chaos in large Boolean networks, Andrew Pomerance, *University of Maryland*

Boolean networks are discrete dynamical systems in which the state (zero or one) of each node is updated at each time t to a state determined by the states at time $t-1$ of those nodes that have links to it. These systems have been extensively studied as models of genetic control in cells and neuronal systems. One important property of these systems is that they exhibit ordered and chaotic dynamics, with a transition between the two regimes. This transition has been well-studied in the limit of random network topologies, however little is known about their behavior in realistic topologies such as those found in biological systems. In this talk we present a criterion that predicts the onset of chaotic dynamics in a wide variety of networks with realistic topological features, such as in-/out-degree correlation, assortativity, community structure, and small motifs. In addition, a generalization of this criterion can be applied to networks with special update rules, such as threshold rules or canalizing rules.

Time delays in the synchronization of chaotic coupled systems with feedback, José Rios Leite, *Universidade Federal de Pernambuco*
Isochrony and time leadership was studied in the synchronized excitable behavior of coupled chaotic systems. Each unit of the system had chaos due to feedback with a fixed delay time. The inter-units coupling signal had a second, independent, characteristic time. Synchronized excitable spikes present isochronous, time leading or time lagging behavior whose stability is shown to depend on a simple relation between the feedback and the coupling times. Experiments on the synchronized low frequency fluctuations of two optically coupled semiconductor lasers and numerical calculations with coupled laser equations verify the predicted stability conditions for synchronization. Synchronism with intermittent time leadership exchange was also observed and characterized [1].

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Effects of Shape on Diffusion, Rob Shaw, *Santa Fe Complex*
The motion of point particles undergoing random motions is well-understood; particle density can be considered a field, governed by the ordinary diffusion equation. The assumption that the infinitesimal particles do not interact leads to densities evolving according to a local and linear differential operator. But as soon as the motions of extended objects are considered, we may see unexpected effects due to nonlocal interactions, and deviations from standard Fickian diffusion. In fact, simple diffusive flow of shapes in confined spaces can be used in the construction of rectifiers, and other machines, on a microscopic scale. This is perhaps relevant in the highly crowded environment of the cytoplasm of living cells. Any sorting, or other operation, which can be accomplished in a simple gradient flow, without the expenditure of ATP, would be highly advantageous. As a particular example, we examine rectification of ion flows in cellular membrane channels. While ion channels in today's living systems are highly sophisticated devices, we show that much of the functionality, including rectification, can be achieved simply with the geometrical constraints arising from extended objects in close proximity. No electrostatic binding, or additional cellular mechanisms are necessarily required. The configuration space of a set of closely packed rigid objects can become convoluted, with many dead-end alleys. If the system is subjected to a shear, or gradient, it may naturally tend to settle in such a dead-end, and have to back up, or retrace its path, in order to proceed further. Thus metastable states, requiring a fluctuation to escape, can commonly arise, and a configuration can become locally locked. The requirement that the system backtrack to unlock distinguishes this process from ordinary jamming. There is no friction per se. We will present simple models of this process. Even a Hamiltonian system of rigid extended objects in equilibrium can have complications. Ergodicity tells us that, in the long run, all configurations must be equally likely. But the space of configurations, subject to boundary conditions, may be constrained. Though the probability of being in any particular configuration is the same, the likelihood of getting in and out of a tight fit can be greatly reduced. For example, an object near a wall or a corner is more likely to remain for a time in a local area than an object in the bulk. Such extended residence times can affect reaction rates of molecules kept in proximity. We will suggest spatially dependent statistics to measure this effect. We will present several examples, including simulations of hard disks in confined geometries, as well as dimers and other shapes moving on a lattice, and a few physical demonstrations.
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Flexibility Increases Energy Efficiency of Digging in Granular Substrates, Dawn Wendell, *MIT*
The mechanics of digging through granular materials often neglect the inhomogeneities present in granular packings. However, this variety of forces implies that there are more and less efficient ways to traverse the granular substrate. This work investigates changes in energy requirements for thin diggers in granular materials by varying the mechanical flexibility of the diggers. We find that there is an optimal amount of

flexibility in the digger that leads to deeper depths than rigid diggers for the same digging energy. Experimental results are compared to theory to explain why flexibility increases digging efficiency.

Posters

Robustness of modular network and overlapping communities, Yong-Yeol Ahn, *Northeastern University*
Our life relies on a wide variety of properly functioning complex systems, from our cells to social organizations. Such complex systems often take the form of network that contains overlapping modules. For instance, the protein-protein interaction network contains protein complexes (modules), which often overlap—sharing elements (proteins). Here, we study the robustness of the networks with functional, overlapping modules using percolation theory. We show that the network of modules may fall apart well before the network of elements does. Our result has important implications on the robustness and dynamics of real-world networks, and may explain how missing information hides pervasive overlap between communities in real networks.

Chaotic Ionization of Bidirectionally Kicked Rydberg Atoms, Korana Burke, *University of California Merced*
A highly excited Rydberg atom exposed to periodic alternating external electric field pulses exhibits chaotic behavior. The ionization of this system is organized by a homoclinic tangle attached to a fixed point at infinity. We present and explain the results from two experiments designed to probe the structure of the phase space turnstile. The first experiment focuses on observing a step-function-like behavior of the ionization fraction as a function of the strength and period of the applied electric field pulses. The second experiment observes the periodic dips in survival probability as a function of the position of the starting electron ensemble in phase space.

Homoclinic Snaking in Plane Couette Flow, John Burke, *Boston University*
Plane Couette flow is a shear flow driven by two parallel plates moving in opposite directions. The simple geometry makes it an ideal system in which to study the transition from a simple laminar flow to complicated turbulent dynamics. On small periodic domains, there are several exact equilibrium and traveling wave solutions to the Navier-Stokes equations which are known to play a key role in guiding this transition to turbulence, and in the turbulence itself. Less is known about the transition to turbulence on larger domains. I describe several new class of exact solutions of plane Couette flow which are spatially localized in one direction, resembling several wavelengths of the known spatially periodic solutions embedded in a laminar background. Under continuation in Reynolds number, the localized solutions exhibit a sequence of saddle-node bifurcations similar to the homoclinic snaking phenomenon, which has been studied extensively in much simpler PDEs such as the Swift-Hohenberg equation. These localized solutions represent a step toward generalizing the dynamical systems picture for turbulence to extended flows. John Burke, Boston University John Gibson, University of New Hampshire Tobias Schneider, Harvard University

Jet-Induced Granular 2-D Crater Formation with Horizontal Symmetry Breaking, Abe Clark, *Duke University*
We investigate the formation of a crater in a 2-D bed of granular material by a jet of impinging gas, motivated by the problem of a retrograde rocket landing on a planetary surface. As the strength and height of the jet are varied, the crater is characterized in terms of depth and shape as it evolves, as well as by the horizontal position of the bottom of the crater. The crater tends to grow logarithmically in time, a result which is common in related experiments. We also observe an unexpected horizontal symmetry breaking at certain well-defined conditions. We present data on the evolution of these asymmetric states and attempt to give insights into the mechanism behind the symmetry-breaking bifurcation. This horizontal symmetry breaking is highly suggestive of a pitchfork bifurcation, and we give evidence to classify it as forward or backward in different regimes of operation. As we will demonstrate, the formation of an asymmetric crater could be of considerable practical concern for lunar or planetary landers, particularly in the case of a backward pitchfork bifurcation, which is characterized by hysteresis and very rapid transitions.

Couette Shear for Elliptical Particles Near

Jamming, Somaiyeh Farhadi, *Duke University*
We have performed 2D Couette shear experiments on systems of photoelastic particles. The particles are identical ellipses with aspect ratio 2. We use the photoelastic property of the disks to obtain the forces acting on a particle. We use two cameras to simultaneously image the particle motion and the photoelastic force response. Using ellipses enables us to understand the effect of particle shape asymmetry on the large-scale behavior on the rheological behavior of granular systems near jamming. Of particular interest are the nematic ordering of the ellipses, the formation of shear bands and the nature of force transmission.

Measuring information flow in anticipatory systems, Daniel Hahs, *US Army RDECOM*
We report that the apparent direction of information flow in an anticipatory (predictive) network depends on measurement resolution. Transfer entropy estimates from low resolution data show net information flow away from an anticipatory element while high resolution measurements show the flow towards it. At low resolutions anticipatory elements will appear to be driving the network dynamics even when there is no possibility of such an influence. Because coarse graining is generally required for the estimation of transfer entropy this effect is likely to be encountered. We present numerical results for coupled maps and analytical results for a Markov chain model and discuss a feature that can be used to detect the presence of anticipatory dynamics.

Experimental and theoretical evidence for fluctuation driven activations in an excitable chemical system, Harold Hastings, *Hofstra University*
An excitable medium is a system in which small perturbations die out, but sufficiently large perturbations generate large "excitations". Biological examples include neurons and the heart; the latter supports waves of excitation normally generated by the sinus node, but occasionally generated by other mechanisms. The ferroin-catalyzed Belousov-Zhabotinsky reaction is the prototype chemical excitable medium. We present experimental and theoretical evidence for that random fluctuations can generate excitations in the Belousov-Zhabothinsky reaction. Although the heart is significantly different, there are some scaling analogies.

Bifurcations of 2D Rayleigh-Taylor Unstable Flames, Elizabeth Hicks, *University of Chicago*
A premixed flame moving against a sufficiently strong gravitational field becomes deformed and creates vorticity. If gravity is strong enough, this vorticity is shed and deposited behind the flame front. We present two-dimensional direct numerical simulations of this vortex shedding process and its effect on the flame front for various values of the gravitational force. The flame and its shed vortices go through the following stages as gravity is increased: no vorticity and a flat flame front; long vortices attached to a cusped flame front; instability of the attached vortices and vortex shedding (Hopf bifurcation); disruption of the flame front by the shed vortices, causing the flame to pulsate; loss of left/right symmetry (period doubling); dominance of Rayleigh-Taylor instability over burning (torus bifurcation); and, finally, complex interactions between the flame front and the vortices. We consider the first few bifurcations of the system in detail. The initial vortex shedding (the Hopf bifurcation) is similar to the first stages of the von Karman vortex street in that both processes are described by the Landau equation. For higher values of gravity, this vortex shedding disturbes the flame front the flame speed begins to oscillate. We show time series analyses of the flame speed for various values of gravity and show that a period doubling bifurcation and a torus bifurcation occur. These bifurcations are related to changes in the behavior of the flame front itself. We also present calculations of the embedding dimension and the largest Lyapunov exponent to help characterize the growing complexity of the system.

Pattern formation in coating flows of suspensions, Justin Kao, *Massachusetts Institute of Technology*
We investigate Landau-Levich coating of a solid wall by a suspension. When the suspended particle size exceeds the liquid film thickness, capillarity induces attractions between particles, and pinning of particles against the wall. Experiments show small-scale clustering of particles, a strongly nonlinear relationship between the particle coating density and the wall speed, and under certain conditions, heterogeneous coating with long-range correlations in the particle density. We show that a continuum model based on the Cahn-Hilliard formalism generates similar behavior.

Spike-Time Reliability of Pulse-Coupled Oscillator Networks, Kevin Lin, *University of Arizona*
A network is reliable if its response to repeated presentations of a given stimulus is essentially repro-

ducible. Reliability is of interest in, e.g., computational neuroscience, since the degree to which a network is reliable constrains its ability to encode information via precise patterns of spikes. In this work, we formulate the problem of reliability using the theory of random dynamical systems. We present an analysis of certain layered network architectures (commonly used in neuroscience), and show how network conditions determine the reliability of such networks.

Depinning of localized structures in a forced dissipative system, Yi-Ping Ma, *University of California, Berkeley*

The 1:1 forced complex Ginzburg-Landau equation (FCGLE) is a forced dissipative system that exhibits bistability between equilibria and thus admits 1D traveling front solutions. A localized state consisting of an inner equilibrium embedded in an outer equilibrium can be formed by assembling two identical fronts back-to-back. The speed of the front can be computed using an ODE in the comoving frame, regardless of the temporal stability of the inner equilibrium in the original PDE. When the inner equilibrium is modulationally unstable, there exists a parameter interval within which the outer equilibrium remains pinned to a periodic state that bifurcates from the inner equilibrium. The bifurcation structure of these steady states is referred to as *defect-mediated snaking* [1]. This growth mechanism nucleates rolls of periodic states at the center of the wave train and thus differs from standard homoclinic snaking where rolls are nucleated at the location of the bounding fronts. Outside the snaking interval, these fronts move (or "depin") such that rolls are created or destroyed via successive phase slips. These phase slips occur in the center of the wave train for slow depinning and off center for fast depinning. Fast depinning is a strongly nonlinear phenomenon that resembles wave propagation confined by an artificial boundary. Slow depinning may be partially explained by a weakly nonlinear theory and reveals subtle differences between the dynamics near the two limits of the snaking interval.

References

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[2] Y.-P. Ma and E. Knobloch, Depinning of localized structures in a forced dissipative system, in preparation (2010).

Clustering of particles in turbulence, Julian Martinez Mercado, *University of Twente*

Preferential concentration of particles occurs frequently in nature, playing an important role in a variety of processes: from cloud formation, sedimentation to plankton distribution in oceans. Even in homogenous isotropic turbulence, particles do not distribute homogeneously. In this work we study particle clustering in homogenous isotropic turbulence both numerically and experimentally. Experiments are carried out in the Twente Water Tunnel. Particle Tracking Velocimetry is employed to obtain 2D and 3D positions of light particles (bubbles). We conduct a Voronoi analysis on the experimental and numerical data to obtain area and volume distributions of the Voronoi cells. From numerics we can also compute these distributions for tracers and heavy particles. Both in numerics and experiments, area and volume distributions show a different behavior from a random Poisson process, implying that clustering is present. In addition, the effect of Stokes number on the clustering behavior can be studied using the numerics.

Invariant manifolds in chaotic advection-reaction-diffusion pattern formation, Kevin Mitchell, *University of California, Merced*

Authors: John Mahoney (UC Merced), Kevin Mitchell (UC Merced), Tom Solomon (Bucknell)

Invariant manifolds are organizing structures central to the problem of transport in chaotic advection, having been applied extensively in periodically driven systems and more recently extended, in the form of Lagrangian coherent structures, to fluids that are not strictly time-periodic. Here, we consider reaction-diffusion dynamics in systems that are simultaneously undergoing chaotic advection. This can be viewed as a simplified model such diverse systems as combustion dynamics in a chaotic flow, microfluidic chemical reactors, and blooms of phytoplankton and algae. Prior experimental and numerical work has shown that such systems generate "burning fronts" with a remarkably rich structure, including the mode locking of the front profile to the driving frequency. Here, we demonstrate how the invariant manifolds useful in chaotic advection can be generalized to accommodate the additional reaction-diffusion dynamics. The generalized manifolds exist in an extended phase space that is of larger dimension than the fluid itself. We show how these manifolds provide a clear criterion for the existence of mode-locking and are essential for explaining the patterns of the mode-locked fronts. Finally, we present recent experimental results on the direct laboratory measurement of such manifolds.

Fluctuations in an agitated granular liquid, Kiri Nichol, *Leiden University / North Carolina State University*
A container of glass beads behaves as a solid - the beads cannot rearrange. However, if the particles are sheared by a spinning disk in the bottom of the vessel the system begins to behave like a liquid: low-density objects float in the grains at the depth predicted by Archimedes' Rule and moving objects experience viscous drag. But what is the microscopic cause of this liquid-like behavior? And does our granular liquid behave microscopically like a real liquid? We have investigated the microscopic behavior of the grains by studying the motion of a probe floating in the grains. The position of the probe fluctuates - and we find that the character of the fluctuations can be Brownian or subdiffusive depending on the shape of the shear band that excites the fluctuations. Finally, we demonstrate that the time scale of the fluctuations sets the time scale of the viscosity, suggesting that fluctuations are the cause of the liquid-like behaviour in sheared granular matter.

Stability and Bifurcations in a Dynamical System Associated with Membrane Kinetics Underlying Cardiac Arrhythmias, Irina Popovici, *USNA*
This presentation aims to describe the bifurcations, stability properties and basins of attraction of a dynamical system introduced by Kline and Baker to model the response to stimulation of a cardiac cell (or electrically coupled multi-cellular preparation). The two-dimensional system is controlled by five parameters: four kinetic parameters (two amplitudes, two rate constants) and the stimulus period. Among periodic orbits, the escalators and the alternans are of particular interest to the medical community. Our results describe their properties, focusing on the impact of varying the stimulus period from slower to faster cardiac rhythms. We also describe bifurcations associated with changing the kinetic parameters within a 4-dimensional region of (mathematically) admissible values, with emphasis on the dissimilarities between the properties of the low order and high-order escalators.

Nonlinear Waves in Granular Crystals, Mason Porter, *University of Oxford*
I will discuss recent investigatations of highly nonlinear solitary waves in granular chains using numerical computations, analytical calculations, and experiments. I will provide an introduction to granular chains, and then I will focus on the dynamics of intrinsic localized modes (aka, discrete breathers) in diatomic chains and chains with defects.

Density-dependent particle clustering on a Faraday wave, Ceyda Sanli, *University of Twente*
Ceyda Sanli, Devaraj van der Meer, and Detlef Lohse. Physics of Fluids Group, Department of Science and Technology, J.M. Burgers Center for Fluid Dynamics and IMPACT, University of Twente, 7500 AE Enschede, The Netherlands.
Floating granular particles on a standing Faraday wave accumulate at the nodal points of the wave due to the wave drift [1]. By the help of the increasing importance of the capillary attraction, in the dense limit the motion of the particles becomes complex. Understanding the resultant spatial distribution of the particles and the clustering is of fundamental importance to characterize such a complex system, and brings a different perspective to the granular flow of particles on surface waves. We experimentally observe that surprisingly the particles position can be changed by increasing the particle concentration. Our hydrophilic naturally buoyant granular particles, clustering at the antinodes for low concentrations, form clusters at the nodes for higher concentrations. Different kind of structures e.g. compact, almost circular clusters, more deformed clusters, such as elongated or filamentary structures, or more heterogeneous patterns are observed at different positions on the wave at an intermediate density of the antinode-node transition. We study the changes in the spatial distribution and the organization of the particles at the antinode-node transition by calculating the Minkowski functionals, which is a powerful technique being used to analyze the geometry and the topology of the pattern formations in e.g. astrophysics, whereas its application grows in various other areas such as biophysics, colloidal physics, and recently in granular physics [2,3]. We apply the Minkowski functionals by considering the point patterns approach: The discs of radius r around each particle center are drawn and then r is varied. We find that it is possible to quantify the different types of clustering by the varieties of decays in the Minkowski functional with respect to r,

e.g. the sharp decays are due to the almost circular clusters, whereas the smooth decays are due to more deformed clusters and heterogeneous patterns.

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[2] K. Michielsen et al. Phys. Reports 347, 461 (2001).
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The Buckley-Leverett Equation with Dynamic Capillary Pressure, Michael Shearer, *North Carolina State University*

The Buckley-Leverett equation for two phase flow in porous media is modified by including a dependence of capillary pressure on the rate of change of saturation. This model, due to Gray and Hassanizadeh, results in a nonlinear partial differential equation. Phase plane analysis, including a separation function to measure the distance between invariant manifolds, is used to determine when the equation supports traveling waves corresponding to undercompressive shocks. The Riemann problem for the underlying conservation law is solved and the structures of the various solutions are confirmed with numerical simulations of the partial differential equation.

Spatiotemporal Dynamics of Calcium-Driven Alternans in Cardiac Tissue, Per Sebastian Skardal, *University of Colorado at Boulder*

Cardiac alternans are a potentially fatal phenomenon defined as a beat-to-beat alternation of action potential duration or calcium concentration in cardiac tissue. Alternans can be either voltage or calcium driven, with distinct qualitative differences in their spatiotemporal dynamics due to the quick diffusion of voltage across tissue. Understanding the spatiotemporal dynamics of alternans in tissue is important because tissue near phase reversals is particularly vulnerable to phenomena like wave break-up and re-entry. Unlike voltage-driven alternans where amplitude equations have been successfully used, for example, to analyze alternans control schemes, the spatiotemporal dynamics of calcium-driven alternans remains poorly understood. We model the coupled dynamics of calcium and voltage alternans in tissue using coupled beat-to-beat continuous maps. These maps include spatial diffusive coupling of voltage and the dependence of signal conduction velocity (CV restitution) on alternans dynamics. We analyze the resulting dynamics numerically and analytically. As the degree of calcium instability is increased, there is a transition from no alternans to smooth traveling waves analogous to that observed in voltage-driven alternans. As the degree of calcium instability is increased further, we observe a novel bifurcation from smooth traveling waves to a stationary discontinuous pattern. This transition is characterized by a boundary layer dividing regions of opposite phase whose thickness decreases, together with the wave velocity, as the transition point is approached. At this point the thickness of this layer and the velocity vanish, and the pattern becomes discontinuous. Scaling predictions for the dependence of the wavelength of smooth and discontinuous patterns of spatially discordant alternans on conduction velocity restitution are derived analytically and verified numerically. Our findings extend our theoretical understanding of spatiotemporal dynamics of alternans to the important case of calcium-driven alternans.

Fingering instability down the outside of a vertical cylinder, Linda Smolka, *Bucknell University*

We present an experimental and numerical study of the dynamics of a gravity-driven contact line of a thin viscous film traveling down the outside of a vertical cylinder of radius R. In all of our experiments with cylinder radii ranging between 0.159 and 3.81 cm, the contact line becomes unstable to a fingering pattern. Observations are compared to inclined plane experiments in order to understand the influence curvature plays on the fingering pattern. Using lubrication theory, we derive a model for the film height that includes gravitational and surface tension effects and examine the structure and linear stability of the contact line using traveling wave solutions. For Bond number (Bo) greater than or equal to order 10 our model predicts that curvature's influence is negligibly weak as the shape and stability of the contact line converge to the behavior one observes for a vertical plane. For Bo greater than or equal to 1.3, the most unstable and cutoff wave modes and maximum growth rate scale like $Bo^{0.45}$, indicating the contact line becomes more unstable as gravitational effects increase or, for a fixed fluid, as the cylinder radius increases. The linear stability of the contact line changes at the critical value $Bo_c = 0.56$, such that, above Bo_c the contact line is unstable and below Bo_c it is stable to fingering. We find excellent agreement between the number of fingers that form along the contact line and the range of wavelengths measured in experiments with the range of unstable modes and wavelengths predicted by our model.

The Buckley-Leverett Equation with Dynamic Capillary Pressure, Kimberly Spayd, *North Car-*

olina State University

The Buckley-Leverett equation for two phase flow in porous media is modified by including a dependence of capillary pressure on the rate of change of saturation. This model, due to Gray and Hassanizadeh, results in a nonlinear partial differential equation. Phase plane analysis, including a separation function to measure the distance between invariant manifolds, is used to determine when the equation supports traveling waves corresponding to undercompressive shocks. The Riemann problem for the underlying conservation law is solved and the structures of the various solutions are confirmed with numerical simulations of the partial differential equation.

Suspensions of Maps to Flows, John Starrett, *New Mexico Institute of Mining and Technology*

The surface of section map is a construction that allows us to analyze certain properties of a flow in n dimensional space by examining a map in $n-1$ dimensions. We can also go the other way by suspending maps to flows, although the utility is not so obvious. We describe several different methods for suspending maps to flows, including the suspension of one dimensional maps to semi-flows equivalent to flows on templates and numerical methods to suspend two dimensional maps to three dimensional flows using only a few carefully chosen periodic points of the map.

The Effect of Network Structure on the Path to Synchronization in Large Systems of Coupled Oscillators, John Stout, *North Carolina State University*

(With Matthew Whiteway)

The Kuramoto Model has been used extensively as a tool for understanding the dynamics of large systems of oscillators that are either coupled globally, locally, or through a complex network. We are interested in the path that systems of networked oscillators take to global synchronization as the coupling strength between oscillators is increased. We employ the Kuramoto Model to study the effects of network size, degree distribution, and natural frequency distribution on the dynamics of these systems. A recent study has shown that small clusters of synchronized oscillators form before the entire system transitions to a state of global coherency. The main result from our work is that this local synchronization is largely independent of both the size and natural frequency distribution of the system, and is instead highly dependent on the average number of links per oscillator, becoming less prominent as this average increases.

Brownian movement in complex asymmetric periodic potential under the influence of "green" noise, Mikhail Sviridov, *Moscow Institute of Physics and Technology*

The idea of the molecular motor has been put forward by M. Smoluchowski and R. Feynman. Up to now this problem has wide development. The physics of this phenomenon consists in different "diffusion velocities" of a Brownian particle in opposite directions if a periodic structure action (for example, a biomolecule or other long chemical chain) is described by a non-symmetric potential. However, for many stochastic systems this problem has still not been treated thoroughly. In particular, we can note that external colored noises are seldom considered. Most often the motion of a Brownian particle is studied for the case when the system is subjected to the action of white noise. However, white noise is just a convenient abstraction for mathematical calculations. In practical situations noise is colored with a spectral density commonly decreasing with frequency. We conditionally call this kind of noise as "red" noise. The well-known red noise is the Ornstein-Uhlenbeck random process. (We are not considering the case of flicker noise). In this work we consider noise when the spectral density of the external broadband noise is equal to zero on the zeroth frequency. In our previous work [1] such a noise is been called as "green" noise. Similar noise can originate if a molecule is lighted by the black-body radiation, or is influenced by thermal phonons noise in low-dimensional structures, or at a phase modulation of a potential, etc. For the analytical study of green noise action, we use an approach based on a Krylov-Bogoliubov averaging method. For the case of green noise this theory is modified to study the action of noise with arbitrary intensity. We show that a certain effective potential can be built which determines the basic features of the system dynamics. Numerical simulations for many systems corroborate this fact. Further, we compare two numerical cases. The first one corresponds to the case of green noise, which is the time-derivative of the Ornstain-Uhlenbeck process. In the second example we take the initial Ornstain-Uhlenbeck process as red noise. We show that there are the complex potentials that the system does not work as a molecular motor in the case of red noise, i.e. the average motion of the particle does not exhibit a drift in a given direction. However, if green noise operates on the same system, the system will play a role of the molecular motor which is effective enough. We demonstrate this fact by a histograms for 100 realisations of these processes.

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Synchronization in Finite-Memory Dynamical Systems, Nicholas Travers, *University of California, Davis*

Nicholas F. Travers and James P. Crutchfield Complexity Sciences Center Mathematics Department Physics Department University of California at Davis Davis, CA 95616

When studying chaotic dynamical systems it is often helpful to use probabilistic models, even if the underlying dynamics are deterministic. In particular, hidden Markov models are often used to model time series data from dynamical systems and subshifts derived from symbolic dynamics. Our work concerns a class of hidden Markov models known as epsilon-machines. Specifically, we are interested in the synchronization problem: How well can an observer infer the internal state of the machine through observations of its output? We find, in general, that an observer synchronizes exponentially fast for any finite-state epsilon-machine. For those that admit a finite-length synchronization word, we provide an analytical method for calculating the synchronization rate. These results have important consequences for prediction: The synchronization rate upper-bounds the convergence rate of finite-length approximations of the Kolmogorov-Sinai entropy. (See http://arxiv.org/abs/1008.4182 and http://arxiv.org/abs/1011.1581.)

Reactive mixing of initially isolated scalars: estimation of mix-down time, Yue-Kin Tsang, *The Chinese University of Hong Kong*

Recently, there is much interest in the chaotic mixing of two reactive scalars that are initially separated by a third inert fluid. Such configuration is relevant to the process of broadcast spawning in marine biology and the modeling of chemical reactions in the atmosphere. The reactants, sperm and egg in the former case and atmospheric chemicals in the latter, are released at separate locations and brought into contact by the flow. An important quantity in this problem is the mix-down time, i.e. time taken for the reactants to come into contact and start to react. Using a Lagrangian chaotic flow, we study the dependence of the mix-down time on the diffusivity of the reactants and the initial separation between them. We shall present a theory relating the mix-down time to the finite-time Lyapunov exponent of the flow.

Stabilization of chaotic spiral waves during cardiac ventricular fibrillation using feedback control, Ilija Uzelac, *Vanderbilt University*

Ilija Uzelac and John Wikswo, Vanderbilt University, and Richard Gray, Food and Drug Adminstration

The cardiac arrhythmias that lead to ventricular fibrillation arise from electrical spiral waves rotating within the heart with a characteristic period tau. A single drifting spiral wave can degenerate into a chaotic system of multiple spiral waves and ventricular fibrillation. Earlier attempts to control cardiac chaos (Garfinkel et al., Science, 1992) utilized the Ott, Grebogi and York (OGY) algorithm (Physical Review Letters, 64: 1196 (1990)) to deliver timed stimuli to a segment of isolated cardiac tissue and convert a drug-induced arrhythmia into periodic beating. However, it is not clear whether this strategy can defibrillate an entire heart. We take an alternative approach wherein early spiral wave detection and termination are used to prevent ventricular fibrillation from developing after the appearance of spiral waves. Time-delayed feedback control (TDFC) is a well known approach for stabilizing unstable periodic orbits embedded in chaotic attractors (Pyragas, Phys. Lett. A, 170: 421 (1992). We hypothesize that an unstable cardiac spiral wave with period tau can be stabilized by applying a TDFC signal that represents the difference between the current state of the system and the state of the system a time tau earlier, weighted by an experimentally obtained scaling factor. Implementing this approach will require precise, closed-loop control of the electrical charge delivered to the heart during the cardioversion/defibrillation process. To do this, we have developed a 2 kW arbitrary-waveform voltage-to-current converter (V2CC) with a 1 kHz bandwidth that can deliver up to 5 A at 400 V for 500 ms, and a photodiode system for recording in real time an optical electrocardiogram, OECG(t). The feedback signal driving the V2CC will be the time-difference (OECG(t) - OECG($t-T$), where we hypothesize that T is τ, the period of the spiral wave. We use phase singularity mapping to identify the appearance of rotors and spiral waves and to verify their stabilization and termination through cardioversion/defibrillation shocks. One limitation of TDFC is a possible sensitivity to the choice of a single feedback delay and amplitude, and it may be necessary to utilize information from many previous states of the system (Pyragas, Phys. Lett. A, 323 (1995)). The advantage of our hardware is that it will be straightforward to implement a variety of algorithms to generate the feedback signal, if necessary with a complex wave form. The TDFC approach may dramatically decrease defibrillation voltages by using a defibrillation waveform that is customized to the particular arrhythmic event, unlike commercial capacitor defibrillation devices with fixed, decaying exponential waveforms. Supported in part by National Institutes of Health grant R01 HL58241-11 through the American Recovery and Reinvestment Act of 2009, and the Vanderbilt Institute for Integrative Biosystems Research and Education.

Dynamic Structure Factor and Transport Coefficients of a Homogeneously Driven Granular Fluid in Steady State, Katharina Vollmayr-Lee, *Bucknell University, USA*

We study the dynamic structure factor of a granular fluid of hard spheres, driven into a stationary nonequilibrium state by balancing the energy loss due to inelastic collisions with the energy input due to driving. The driving is chosen to conserve momentum, so that fluctuating hydrodynamics predicts the existence of sound modes. We present results of computer simulations which are based on an event driven algorithm. The dynamic structure factor $F(q,\omega)$ is determined for volume fractions 0.05, 0.1 and 0.2 and coefficients of normal restitution 0.8 and 0.9. We observe sound waves, and compare our results for $F(q,\omega)$ with the predictions of generalized fluctuating hydrodynamics which takes into account that temperature fluctuations decay either diffusively or with a finite relaxation rate, depending on wave number and inelasticity. We determine the speed of sound and the transport coefficients and compare them to the results of kinetic theory.

Entrainment of a Thalamocortical Neuron to Periodic Sensorimotor Signals, Dennis Guang Yang, *Drexel University*

We study a 3D conductance-based model of a single thalamocortical (TC) neuron in response to sensorimotor signals. In particular, we focus on the entrainment of the system to periodic signals that alternate between 'on' and 'off' states lasting for time T_1 and T_2, respectively. By exploiting invariant sets of the system and their associated invariant fiber bundles that foliate the phase space, we reduce the 3D system to a 2D map, based on which we analyze the bifurcations of the entrained limit cycles as the parameters T_1 and T_2 vary.

A mathematical model of the decline of religion, Haley Yaple, *Northwestern University*

People claiming no religious affiliation constitute the fastest growing religious minority in many countries throughout the world. Americans without religious affiliation comprise the only religious group growing in all 50 states; in 2009 those claiming no religion rose to 15 percent nationwide, with a maximum in Vermont at 34 percent. Here we use three simplified models of competition for members between social groups to explain historical census data on the growth of religious non-affiliation in nine countries worldwide. All three models coincide in the limit of an all-to-all social network, but surprisingly, perturbations dividing the network into cliques do not change the qualitative dynamics. According to these models, a single parameter quantifying the perceived utility of adhering to a religion determines if the unaffiliated group will grow in a society. The models predict that for societies in which the perceived utility of not adhering is greater than the utility of adhering, religion will be driven toward extinction.

Switching from steady-state to chaos via pulse trains in an optoelectronic oscillator, Kristine Callan, *Duke University*

Authors: Kristine E. Callan, Lucas Illing, David Rosin, Daniel J. Gauthier, and Eckehard Schöll

We investigate an optoelectronic oscillator comprised of commercially available components which, due to the presence of a feedback loop and nonlinear element, displays a variety of dynamical behaviors [1, 2]. For a particular choice of slope of the nonlinearity, the (noise-free) model describing our system shows that the steady-state is linearly stable for all values of the feedback gain. We find, however, that this quiescent state coexists with a chaotic attractor. One can switch from the quiescent state to the chaotic with a finite-size perturbation, causing the production of an initially periodic train of pulses spaced by the time-delay of the feedback loop with a pulse duration (full width at half maximum) of less than 200 ps. Eventually, the pulse spacing and amplitude become irregular, resulting in fully developed broadband chaos with a featureless power spectrum. We derive a one-dimensional map that accurately predicts the amplitude of the perturbation necessary to push the system to the coexisting chaotic attractor, via a pulse train, as a function of the feedback gain. For a given noise level, this map also predicts the value of the gain for which the system leaves the quiescent state for all operating points of the nonlinearity. This result could have general implications for the stability of time-delay systems, for which coexisting states are common. In addition, the system's propensity for producing periodic trains of pulses is also being investigated further, and stable pulsing solutions with durations of less than 200 ps have been realized experimentally.

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Brownian Motion By Switching Unstable Dissipative Systems, Eric Campos Cantón, *Instituto Potosino de Investigación*

It is known that the Brownian motion is the movement generated by a particle suspended in a fluid. Then, the Brownian motion of a particle under the same condition has to behave identically, and the behavior just chance if the initial conditions chance. Thus, we address the following question: Is the Brownian motion a chaotic or random process? There are two comments: The first comment is about that the Brownian motion has been modeled as a stochastic process because it is easy to model a process where nobody knows what happen in the collision between particles. The second comment, the collision between two particles can be modeled and it is a deterministic process, so the collision between several particles is a deterministic process too. Then if we know the exact number of collision between the particle and others we will be able to model the exact trajectory of the particles. It is found that, in general, Chua's trajectories behave as a Brownian motion for small time scales, while they can display a white noise-like behavior or be dominated by harmonic oscillations for large time scales. The Chua's system is a PWL system which yields two scrolls. The generalization of PWL system can be seen in [1, 2]. The aim of this work is to introduce Brownian motion as the central object of deterministic process and discuss its properties, putting particular emphasis on the sample path properties. Switching piece wise linear systems exhibit a chaotic behavior reflected by a strong divergence of trajectories with arbitrarily close initial condition. In this way, similar to trajectories from Brownian motion, chaotic trajectories by PWL systems can be seen as noise with some degree of correlation. This work focuses on the study of chaotic behavior with similar properties that Brownian motion. The chaotic time series are studied by using detrended fluctuation analysis and wavelet transform, which are a methods designed for the detection of correlations in stochastic time series.

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Phase space method for target ID, Thomas Carroll, *Naval Research Lab*

Chaotic signals are very sensitive to the effects of filtering. In radar or sonar, scattering from a target is a linear process that may be described as a filter. I have found that interaction of a chaotic signal with a target produces a characteristic distribution of neighbors in phase space which may be used to identify the target. The particular distribution of points depends on the rate of compression for the chaotic signal and on the target characteristics. I show results of numerical simulations and simple microwave experiments.

Hamiltonian monodromy, Chen Chen, *College of William and Mary*

We say that a system exhibits monodromy if we take the system around a closed loop in its spectrum space, and we find that the system does not come back to its original state. We report a method for experimental realization of a newly discovered dynamical manifestation of monodromy by investigating the behavior of atoms in a trap. The trapping potential has long range attraction to and short range repulsion from the center. Calculations include two parts. First, we consider atoms as classical particles for which we can choose any desired set of initial conditions. As was shown previously for different systems, when we take the system around a monodromy circuit, a loop of initial conditions evolves into a topologically different loop. Second, we incorporate the limitations that would appear in experimental implementation. The atoms have a range of initial angles, initial angular momenta, and initial energies. Our work shows how real atoms can be driven by real forces around a monodromy circuit, and thereby shows how one can observe dynamical monodromy in a laboratory. Finally, we extend classical dynamical monodromy to quantum dynamical monodromy by examining wave function evolution under comparable conditions.

Exploring the dynamics of CRISPR loci length: How much can a bacterium remember about viruses that infected it?, Lauren Childs, *Georgia Institute of Technology*
A novel bacterial defense system against invading viruses, known as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), has recently been described. Unlike other bacterial defense systems, CRISPRs are virus-specific and heritable, producing a form of adaptive immune memory. Specific bacterial DNA regions, CRISPR loci, incorporate on average 30 copies of unique short (20 base pair) regions of viral DNA which then allow the bacteria to detect, degrade and have immunity to viruses with matching sub-sequences. Ideally, the number of unique viral-copied regions a bacterial CRISPR loci contains would grow indefinitely to allow immunity to a large number of viruses. However, the number of these short viral-copied regions in the CRISPR loci of any bacteria appears to be limited. We use a birth-death master-equation model to explore the growth and decay of the length of the CRISPR loci and thus the number of short viral-copied regions.

The role of crossover recombination, inversion, and gene linkage in determining gene spacing in a chromosome., Brian Clark, *Illinois State University*
The human genome consists of approximately 30,000 genes and other elements of DNA distributed over 23 pairs of chromosomes. Genes may be linked together in so far as they code for proteins that taken together can represent a single trait. Here we examine the role of crossover recombination between individual strands of DNA and inversion within a single strand of DNA in determining the spacing between two genes linked through their fitnesses via a computational simulation. Our model includes a population of haploid individuals with n genes per single strand of DNA. Two of the genes are linked through their fitness function, which can be additive, multiplicative, stochastic, or constant. Individuals are allowed to reproduce according to a function of their fitnesses. When two individuals are selected for reproduction, they each undergo an inversion with rate Ri and then are allowed to crossover with rate Rc. Only offspring with two genes for the specified trait survive reproduction. We record the changes in gene spacings as the system evolves and show that the system has a small number of attractors who's stability is a function of inversion and crossover rates. We also show that genes linked with multiplicative fitnesses are more likely to be found closer together than genes linked with additive fitnesses, when starting from a specific set of initial gene positions.

Bifurcations from sub-wavelength changes in a wave chaotic cavity with nonlinear feedback, Seth Cohen, *Duke University*
Seth D. Cohen, Hugo L. D. de Souza Cavalcante, Daniel J. Gauthier, Department of Physics, Duke University, Durham, NC, USA
Broadband chaos has been observed previously in a simple transistor-based nonlinear circuit with time-delayed feedback through a single coaxial cable [1]. We replace this coaxial cable with a multipath delay system consisting of broadband antennas placed inside a stadium-shaped cavity. This creates a new nonlinear feedback system where the multipath reflections of the radio waves inside the cavity become the delayed feedback loops of the dynamical system. By translating the location of a sub-wavelength scatterer that is also placed in the cavity, the path lengths and coupling strengths of these feedback delays change. From scatterer movements as little as 10 micrometers, we observe bifurcations in the system?s output voltage between periodic, quasi-periodic, and chaotic attractors. The primary purpose of this work is to describe the bifurcations observed in this multipath, time-delay dynamical system. The minimal detectable change in scatterer position is 15,000 times smaller than the minimum wavelength of radiation inside the cavity (15 cm). By exploiting this novel technique for sub-wavelength sensitivity, we hope to improve traditional methods of intrusion detection systems and tracking devices with through-wall capabilities. We gratefully acknowledge the support of the ONR MURI “Exploiting Nonlinear Dynamics for Novel Sensor Networks”.
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Exact Folded-Band Oscillator, Ned Corron, *US Army RDECOM*
We present a novel, low-dimensional chaotic oscillator that exhibits an exact folded-band attractor.

That is, analytic returns of the oscillator waveform exactly satisfy a one-dimensional, unimodal map. The oscillator is a hybrid dynamical system including both a continuous differential equation and a discrete switching condition. Between switching events, the oscillator is linear and solvable, and we derive an exact analytic expression relating peak returns. For this oscillator, we find the successive maxima return map is conjugate to a one-dimensional skew tent map, thereby proving the waveform is chaotic and characterized by a simple, noninvertible fold. Furthermore, the chaotic waveform admits a linear representation using a fixed basis pulse, for which a simple matched filter is defined. As such, we claim this oscillator is well suited for chaotic radar and communication applications, and we show a physical realization as an electronic circuit. Experimental data is presented that confirms the effectiveness of the physical implementation.

Electroporation in a three-dimensional, time-dependent model of a skeletal muscle fiber, Jonathan Cranford, *Duke University*

Electroporation, in which strong electric pulses create transient pores in the cell membrane, holds promise for improving delivery of DNA to skeletal muscle fibers in gene therapy applications. However, the results of electroporation-mediated gene delivery in fibers are difficult to predict, as electroporation is a nonlinear process. Current models of fibers assume that electroporation is proportional to the magnitude of only the transverse component of the electric field. This study investigates the full spatiotemporal dynamics of electroporation using a new time-dependent model of a 3-D muscle fiber. The model assumes a cylindrical fiber and two point source electrodes positioned parallel to the fiber in an isotropic conductive solution. The membrane of the fiber responds to strong transmembrane potential (V_m) by developing electropores at a rate that is an exponential function of the square of V_m. The model accounts for the creation of electropores by solving at each location on the fiber membrane an ODE that governs pore density N. Outputs of model simulation are the time evolution of V_m and N over the entire fiber membrane, which are compared to electroporation predicted from a linear, non-electroporating version of the model. The linear model shows that the largest magnitude of V_m and the largest region of elevated V_m occur on the side of the fiber facing the electrodes. Thus, the linear model implies that both the pore density N and the region of elevated N should be greater on the side of the fiber facing the electrodes. However, the nonlinear model shows that the magnitudes of V_m and N are approximately equal at the sides of the fiber facing and opposite to the electrodes, and that the region of elevated N is greater at the side of the fiber opposite to the electrodes. Therefore, the nonlinear model of an electroporating fiber produces different results than the linear, non-electroporating model.

Force Network in a 2D Frictionless Emulsion Model System, Kenneth Desmond, *Emory University*

We confine oil-in-water emulsion droplets between two parallel plates to create a quasi-two-dimensional model system to study the jamming transition. This model system is analogous to granular photoelastic disks with the exception that there is no static friction between our droplets. To study the jamming transition we compress the droplets in small increments and investigate how the force network evolves with increasing area fraction, where the forces are measured using a calibration technique we have developed. The forces in our system are spatial heterogeneous with a probability distribution that is similar to that found for photoelastic disks. We also find that the probability distribution of the forces narrows with area fraction, and that the correlation length of the largest forces is only few particle diameters.

Homogeneous linear shear of a two dimensional granular system, Joshua Dijksman, *Duke University*

Using a novel shear device, we experimentally study the response of dry granular materials to quasi-static shear. Our apparatus is capable of creating linear strain profiles over the entire width of the two dimensional shear cell. By eliminating the usual tendency of granular shear to localize in non-uniform shear bands, we can study the poorly understood nature of granular flows in great detail. We employ photo elastic particles, fluorescent labelling and high resolution imaging to obtain information about particle positions, rotation and inter particle forces. We discuss our results in the context of the jamming scenario and also look at various measures capable of elucidating the physics of dense granular flows.

An Information-Theoretic Analysis of Competing Models of Stochastic Computation, Christopher Ellison, *UC Davis*

Finitary, stationary stochastic processes are analyzed in terms of the convergence of state-block and block-state entropies. The latter are compared to previously known convergence properties of the Shannon block entropy. We find that synchronization is determined by both the process's internal organization and by an observer's model of it. With regard to the choice of model, a natural classification scheme is defined in terms of minimality, synchronizability, and unifilarity. In particular, we characterize information in the model that is not justified by the data—gauge information—and asymptotically inaccessible information encoded about the future—oracular information. Finally, we draw out a duality between synchronization properties and a process's controllability. (See arXiv:1007.5354.)

Universal Shapes Formed by Two Interacting Cracks, Melissa Fender, *NCSU*

Brittle failure through multiple cracks occurs in a wide variety of contexts, from microscopic failures in dental enamel and cleaved silicon to geological faults and planetary ice crusts. In each of these situations, with complicated curvature and stress geometries, pairwise interactions between approaching cracks nonetheless produce characteristically curved fracture paths known in the geologic literature as en passant cracks. While the fragmentation of solids via many interacting cracks has seen wide investigation, less attention has been paid to the details of individual crack-crack interactions. We investigate the origins of this widely observed crack pattern using a rectangular elastic plate which is notched on each long side and then subjected to quasistatic uniaxial strain from the short side. The two cracks propagate along approximately straight paths until the pass each other, after which they curve and release a lenticular fragment. We find that, for materials with diverse mechanical properties, the shape of this fragment has an aspect ratio of 2:1, with the length scale set by the initial cracks offset s and the time scale set by the ratio of s to the pulling velocity. The cracks have a universal square root shape, which we understand by using a simple geometric model and the crack-crack interaction.

Applying the Loschmidt Echo and Fidelity Decay to Classical Waves in a Wave Chaotic System with a Nonlinear Dynamic Response, Matthew Frazier, *University of Maryland, College Park*

The quantum mechanical concepts of Loschmidt Echo and Fidelity measure the effect of perturbations on the quantum wave system. In previous work, we extended these concepts to classical waves, such as acoustic and electromagnetic, to realize a new remote sensor scheme [1, 2]. The sensor makes explicit use of time- reversal invariance and spatial reciprocity in a wave chaotic system to sensitively and remotely measure the presence of small perturbations to the system. The loss of fidelity is measured through a classical wave-analog of the Loschmidt echo by employing a single-channel time-reversal mirror to rebroadcast a probe signal into the perturbed system [3]. The operation of the time-reversal mirror itself benefits from the wave chaotic scattering in the system. We compare and contrast the detection power and computational efficiency of our sensor with other techniques such as correlation and/or mutual information of probing signals. We also introduce the use of exponential amplification of the probe signal to partially overcome the effects of propagation losses; on the other hand, time windowing of the probe signal, along with the exponential amplification, is demonstrated to be effective to vary the spatial range of sensitivity to perturbations, and the extent to which the spatial range of the sensors can be varied is discussed. Experimental results are presented for the acoustic version of the sensing techniques studied. Now, we take this work in a different direction by considering the case in which there is a device with a nonlinear response inside a wave chaotic electromagnetic system. In addition to the chaos that emanates from the sensitive dependence of the ray trajectories to initial conditions, there is now a classical nonlinearity in the system that creates new responses. Preliminary results of this modification to our existing work are also presented. Work funded by ONR MURI grant N000140710734, the AFOSR under grant FA95501010106, and by the IC Post-Doc program.

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Evolutionary stability of an optimal strategy for habitat selection, Theodore Galanthay, *University of Colorado - Boulder*

Ecologists have long sought to make sense of the observed distributions of organisms. In the majority of these theoretical habitat selection models, scientists have assumed that organisms move in response to fitness differences between patches (for discrete space models) or a fitness gradient (in continuous space models). More recently, scientists studying habitat selection have recognized the importance of incorporating in models the individual behavioral forces that influence these population distributions. While it is widely assumed in habitat selection models that individuals move to maximize their fitness, it remains unclear what type of movement mechanisms might in fact produce higher fitness. We ask what type of movement mechanisms might lead to higher fitness by analyzing a mechanistic single-species two-patch habitat selection model. We compute analytically a movement strategy that demonstrates that higher fitness is not achieved by moving solely in response to fitness-dependent cues. We show that this evolutionarily stable strategy (ESS) is a continuously stable strategy (CSS). We propose that there might exist a movement strategy that is a blend of random, fitness-dependent, and habitat-dependent movement that maximizes a species' fitness. Therefore, we consider three different movement mechanisms: discrete diffusion, fitness-, and habitat-dependent movement. We ask, is it evolutionarily advantageous for a species to move based on fitness (i.e. per capita reproductive growth) differences, habitat differences, or a mixture of these? We use standard evolutionary game theory to find the answer to this question. We discover a candidate evolutionarily stable strategy for a discrete two-patch habitat system and apply the tools of adaptive dynamics to show by numerical simulation that this strategy is an ESS and also convergence stable.

Quantifying the Complexity of Kauffman Networks, <u>Xinwei Gong</u>, *Duke University*
In a 2004 article, Shalizi et al proposed a statistical measure that quantifies the complexity of spatially-extended dynamical systems. They define complexity as the amount of information required for optimal prediction of system's dynamics, and describe an algorithm for measuring the complexity given time series data for all components in a discrete system. The results of applying the algorithm to 1D and 2D cellular automata agree with intuitive expectations. We study this complexity measure for random Boolean networks in which every node has an indegree and an outdegree of 2. We show that for a given distribution of logic functions, the complexity is a function of the steady-state bias of the network and not simply related to its sensitivity to perturbations.

Subrcritical Fracture of Porous Media, <u>Alessio Guarino</u>, *Université de la Polynésie Française*
We study the lifetime of a porous media submitted to a constant subcritical stress. We present a model based on a 2D spring network with thermal fluctuations were the porosity is represented by missing springs. Numerical results are compared to experimental data of fracture of porous media submitted to three-point flexion.

Dynamic Modeling and Simulation of a Real World Billiard, <u>Alex Hartl</u>, *North Carolina State University*
Alex Hartl, North Carolina State University Bruce Miller, Texas Christian University Scientists are interested in gravitational billiards since they exhibit a variety of dynamical phenomena in nonlinear Hamiltonian systems. The system typically consists of a particle undergoing elastic collisions within a boundary, where the particle follows a ballistic trajectory between collisions. This paper considers the more realistic situation of an inelastic, rotating, gravitational billiard in which there are retarding forces due to air resistance and friction. In this case the motion is not conservative, and the billiard is a sphere of finite size. Here we present a dynamical model that captures the relevant dynamics required for describing the motion of a real world billiard for arbitrary boundaries. An application of the model considers parabolic, wedge and hyperbolic billiards that are driven sinusoidally. Direct comparisons are made between the model's results and experimental data previously collected. Although several studies have investigated the effect of variable elasticity in relation to the gravitational billiard, this study is the first to incorporate rotational effects and additional forms of energy dissipation.

Chaos in semiconductor at hellical instability, <u>Khadjimurat Ibragimov</u>, *Institute of Physics Daghestan Sc. Centre of Russian A. S.*

Isochronous chaos synchronization of delay-coupled optoelectronic oscillators, <u>Lucas Illing</u>, *Reed College*
We study experimentally chaos synchronization of nonlinear optoelectronic oscillators with time-delayed mutual coupling and self-feedback. A single such optoelectronic oscillator can generate a wide range of dynamical behaviors, including fast and high-dimensional chaos. Coupling three oscillators in

a chain, we find that the outer two oscillators always synchronize isochronally. In contrast, isochronous synchronization of the mediating middle oscillator is found only when certain matching conditions for the time delays and coupling strengths are satisfied. Our experimental results are in good agreement with theory.

Quantum and classical pumping using ultracold atoms, Megan Ivory, *College of William and Mary* Can electrons be pumped from one reservoir to another without a difference in the electrical potential? Various theoretical schemes have been predicted, but no experiments have successfully implemented them. We examine the analogous question for neutral particles: can ultracold atoms be pumped from one reservoir to another without an external potential difference? We are running numerical simulations to identify experimental schemes which are capable of yielding large currents using time-varying potential barriers or wells in the channel connecting the reservoirs. Our simulations use either quantum or classical mechanics, and explore symmetric and anti-symmetric double barrier and double well pumps with rectangular and Gaussian potentials. We show that for a non-uniform distribution of initial momentum, we can expect significant classical pumping in addition to quantum pumping. Also, in some regions, the dynamics show sensitive dependence upon initial conditions, and regions of fractal behavior are evident. We present preliminary results for various schemes, and suggest experimental parameters for testing the theoretical predictions using ultracold atoms.

Application of periodic orbit theory to chaos computing, Behnam Kia, *Arizona State University* Chaos computing is introduced as a method to construct functions based on intrinsic complicated dynamics of chaotic systems. The data inputs are encoded as the parameters or the initial conditions of a chaotic dynamical system and the resulting system state represents the output of the computation. By controlling how inputs are mapped to outputs, a specific function can be constructed. So far no clear connection has been demonstrated between the structure of the dynamics and the computation that the dynamical system can perform. In this poster we describe, model and predict chaos computing based on the dynamics of the underlying chaotic system. Here we model the dynamical system by use of its basic unstable periodic orbits (UPOs). Then we use these UPOs and their stability in terms of eigenvalues to obtain the functions that the chaotic system can construct and also to estimate the stability of these functions against noise.

Pattern formation of grains in oscillatory frluid flows, Daphne Klotsa, *University of Bath* Granular experiments in oscillatory fluids have been observed to form patterns dominated by hydrodynamic interactions [1,2]. We are studying a system consisting of a collection of macroscopic stainless steel spheres undergoing horizontal vibration in a Newtonian fluid at intermediate Reynolds numbers (between 5-200). The particles are initially in a dispersed configuration and evolve into an ordered chain structure, aligned perpendicular to the direction of oscillation. We have developed computer simulations to model such a system and have validated them against experiments. The nonlinear average fluid flow (steady streaming) around pairs and chains of interacting particles has been computationally calculated and shown to be the driving force behind the pattern formation.

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Understanding the Dynamics of Flames using Time Series Analysis, Christopher Kulp, *Lycoming College* Proper balancing of air-fuel mixing is one of the most important factors in designing and controlling high efficiency, low-emission burners for process heat and power production. As utilization of alternative non-petroleum-based fuels has increased (especially biomass derived fuels) in boilers, engines, and gas turbines, the need to develop improved burner diagnostics and controls to maintain high efficiency and minimum emissions of pollutants and greenhouse gases has escalated significantly. In this poster, we present preliminary results in our work to develop simple algorithms and models for using video imaging to measure and understand the dynamic state of gas-air flames as key burner parameters are adjusted. In particular, we are interested in understanding how the spatio-temporal behavior of these flames changes as the air-to-fuel ratio (AFR) is varied through critical values (e.g., the stoichiometric point), where major global shifts in the dynamics are known to occur. We are interested in quantitatively tracking those changes with optical sensors (e.g., digital videography) and developing approaches for real-time feedback controls. In the present experimental work, we record video images of flames from a gas-air Meker burner with a fixed AFR and with a slowly changing AFR. We generate time series from the video recordings and perform various statistical analyses to which describe the state of the flame during the video. In this poster, we explain how we generate time series from the video and show some preliminary statistical results.

A new algorithm for detection of apnea in infants in neonatal intensive care units, Hoshik Lee, *College of William and Mary*
Apnea is a very common problem for premature infants: apnea of prematurity (AOP) occurs in $> 50\%$ of babies whose birth weight is less than 1500 g, and AOP is found in almost all babies who are $<$ 1000g at birth. Current respiration detectors often fail to detect apnea, and also give many false alarms. We have created a new algorithm for detection of apnea. Respiration is monitored by continuous measurement of chest impedance (CI). However, the pulsing of the heart also causes fluctuations in CI. We developed a new adaptive filtering system to remove heart activity from CI, thereby giving much more reliable measurements of respiration. The new approach is to rescale the impedance measurement to heartbeat-time, sampling 30 times per interbeat interval. We take the Fourier transform of the rescaled signal, bandstop filter at 1 per beat to remove fluctuations due to heartbeats, and then take the inverse transform. The filtered signal retains all properties except the impedance changes due to cardiac filling and emptying. This proves particularly effective during some severe episodes of apnea. While the infant is not breathing, the reduced oxygen levels slow the heart rate considerably, and the increased volumes of blood during each cycle lead to sizable changes in impedance that can be mistaken for breaths by the conventional detection algorithms. The clinical result is that the monitor reports that the breathing rate is equal to the heart rate when in fact there is no breathing at all. We use the new algorithms as a basis for detecting apneas in a large and growing data set from the University of Virginia Neonatal Intensive Care Unit, and we study apnea characteristics in a variety of clinical scenarios.

Symmetry and Stability in Network Dynamical Systems, Anika Lindemann, *Colby College*
In the study of network dynamical systems, the theorems of linear algebra enable us to connect local structural properties to the dynamical properties of the network as a whole. In particular, for the case of symmetric networks, we can identify structural motifs that confer instability to the entire network; addition or removal of other pieces of the network cannot restore stability. For networks with simple edge-weight distributions, these motifs lead to a complete characterization of stability. In this presentation, we will outline these theoretical discoveries and discuss their application to more general networks.

Probabilistic Maxima in Basins of Attraction of Coexisting States in a Noisy MultistableSystem, Brenda Martinez, *Universidad de Guadalajara*
When talking about the size of the basins of attraction of coexisting states in a noisy multistable system, one can only refer to its probabilistic properties. In this context, the most probable size of basins of attraction of some coexisting states exhibits an obvious maxima with respect to the noise amplitude. The evidence of this maxima is demonstrated through the study of the Hénon map with three coexisting attractors: period 1, period 3, and period 9. By applying periodic modulation to a system parameter, we find the connection between this resonance and the fundamental frequency of the corresponding attractor. Noise, periodic modulation, and a combination of both can provide an efficient control of the global structure of phase space of a system with multiple coexisting attractors.

Pinned and Twisted Scroll Rings in an Excitable Chemical System, Bradley Martsberger, *Duke*
Authors: B. Martsberger, Z. Jimenez, O. Steinbock
Three dimensional spiral waves, called scroll waves, rotate around a one-dimensional space curve called a filament. In some cases a filament may form a closed loop. Typical long term behavior of a closed loop scroll ring is a complete collapse leading to the extinction of the scroll wave. In media containing unexcitable heterogeneities, all or some part of the filament can become attached to the heterogeneity preventing the collapse of the spiral. Such phenomenon has been observed in cardiac systems. In the case where a portion of the filament is pinned, rotation frequency differences create stationary gradients in the rotation phase, called twist. Twist patterns and their frequencies agree with solutions of the forced Burgers' equation revealing insights into the nonlinear phase coupling of scroll waves.

Localization phenomena arising from spatially pe-

riodic forcing, Jonathan McCoy, *Colby College*
Localized structure formation is a striking feature of many spatially extended nonlinear systems. We find, in an experiment on spatially periodic forcing of thermal convection patterns in a large aspect ratio fluid layer, that frustration arising from the forcing generates an unexpected assortment of kink, ringlet, and worm structures. In this presentation, we offer a unified interpretation of these localized pattern motifs and explore its consequences for our understanding of the transition to spatiotemporal chaos. This work was supported by the National Science Foundation under grant no. DMR-0305151 and by the Max Planck Society.

Instability in a Sheet of Birds, Nicholas Mecholsky, *University of Maryland*
Flocks of birds and other aerial animals are often observed in coordinated sheets of individuals that can move wildly in the air. This poster investigates such sheet-like behavior. Using a continuum model for a flock of individuals, we find equilibria where the density goes to zero at a finite extent for several different forms of the pressure. We then investigate the stability of a sheet of individuals. We find that motion of the flock along the direction of the sheet is always unstable for the pressures that we investigate.

Control of chaos by a weak perturbation in an impact oscillator., Everton Medeiros, *Universidade de São Paulo*
We control chaotic orbits in an impact oscillator by applying a weak periodic perturbation. The parameters of the controlled periodic orbits compose new periodic windows in the bi-dimensional parameter space. These new periodic windows are displaced in the parameter space by varying the perturbation amplitude. We identify periodic and chaotic attractors by their largest Lyapunov exponents.

Estimating the time scales for the evolution of robustness under almost-neutral drift, Garrett Mitchener, *College of Charleston*
Many biochemical mechanisms are robust: multiple reactions serve to control them, so a mutation that damages one reaction but leaves others intact leaves the organism fully functional. Abstractly, consider a species with some beneficial feature whose mechanism is vulnerable to a mutation. The two phenotypes are identical except for a slight difference in the quality of their offspring, so natural selection will be unable to distinguish them on short time scales, hence the term "almost-neutral drift". A different mutation that makes the mechanism more robust could take over the population. Let us define the terms 'type 0' for the baseline genotype, 'type 1' for a genotype that has an advantageous feature but is one mutation away from losing it, and 'type 2' for a genotype that has the same feature and is robust against a single mutation. We are interested in what happens to a population of mostly type 1 agents with minority of type 2 agents. A Markov chain can represent these dynamics on a finite population exactly. It turns out to be rather likely that starting from a single type 2 agent in a population of all type 1, the robust form will go extinct, after which the advantageous feature will eventually go extinct as well. However, conditioned on the event that the robust form does take over, it takes on average a relatively short time to do so. Furthermore, details of the selection-mutation algorithm have a significant impact on these results. I will present numerical and theoretical results for the circumstances under which the protective mutation takes over the population based on these models

Application of Nonlinear Data Analysis to Locating Disease Clusters, Linda Moniz, *Johns Hopkins University*
This research centers on a new definition of a disease cluster and detection of these clusters in real time series of counts of clinic visits for respiratory ailments. Previous definitions of clustering concentrated on the spatial definition (coincident detection) and ignored the dynamical one (shared dynamics between locations). Thus, many statistical methods for finding disease clusters are prone to false alarms when the detection thresholds are tuned to high sensitivity. We show that our new definition of clustering together with a three-stage detection method can differentiate between actual clusters and geospatially coincident detections. This is preliminary research intended for proof-of-concept but shows that the method is promising; it has high sensitivity and fewer false alarms than a current "state of the art" method for detecting disease clusters.

Robustness of multi-layer networks composed of mixed oscillators, Kai Morino, *The University of Tokyo*
Kai Morino, Gouhei Tanaka, and Kazuyuki Aihara
Coupled oscillators have been used to understand many real-world phenomena, e.g., behaviors in networks of biological oscillatory elements. Since living things eventually die and lose their activity, be-

haviors of mixed populations composed of active and inactive elements are interesting phenomena. Daido and Nakanishi investigated globally coupled networks composed of active and inactive oscillators [1]. They found an aging transition: when the proportion of inactive oscillators in the total population increases beyond a critical value, global oscillations vanish away. Following this seminal work, aging transitions in networks composed of several elements have been studied with homogeneous structures. However it is known that many biological networks are heterogeneous, for example, the cortical column with a multi-layer structure. Therefore it should be important to investigate the aging transition in heterogeneous networks. The critical value of the aging transition point can be associated with a degree of robustness to changes of network elements from active to inactive. In our study, we investigate the robustness of multi-layer networks with mixed populations through aging transitions. We show that networks increase or decrease their robustness depending on interlayer couplings. In addition, we find that an increase of mismatches of oscillator types (active or inactive) among locally connected oscillators reduces the robustness of the networks with mean field, chain, and diffusion couplings. Moreover, we discuss the robustness of networks with more than two layers. This research is partially supported by the FIRST program from JSPS.

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Noise-induced Phenomena in Two Strongly Pulse-coupled Resonate-and-Fire Neuron Models, Kazuki Nakada, *Kyushu Institute of Technology*

In this work, we consider the effects of dynamical noise in a continuous dynamical system on its discrete return map. Specifically, we have analyzed a system of two pulse coupled resonate-and-fire neuron (RFN) models and the synchronization phenomena and chaotic behavior by using Firing Time Difference Map (FTDM), which is the return map constructed from one dimensional maps with regard to the firing time difference between two RFN models. We firstly demonstrate that the global stability of burst synchronization in anti- and out-of-phase and Type I intermittent chaos. Secondly, we show noise-induced phenomena occurs in the system with additive white Gaussian noise on threshold voltage. Finally, we consider the the robustness of chaos in biological neurons.

Intermittent Jamming in Quasi-2D Microfunnels Carlos Ortiz, *North Carolina State University*

Both athermal granular jamming and thermal glass transitions have recently received extensive attention. We experimentally investigate the jamming transition in a quasi-2D system of nearly hard-sphere, micron-sized particle suspension in a density and index-matched medium flowing through a microfunnel. We observe the packing fraction driven transition from a gas-like to a liquid-like to a solid-like phase. At sufficiently high packing fractions we observe intermittent jamming under constant pressure driving. Further increase in the packing fraction forms a stable solid-like jammed phase which is disordered on long-ranges, and susceptible to remelting by reverse flow, agitation, and diffusion. By displaying properties of both athermal granular jamming and thermal glass transitions, our experiment provides a useful testing ground for understanding the jamming transition as a unifying framework.

The effect of force chains on near-field sound propagation, Eli Owens, *North Carolina State University*

Granular materials are inherently heterogeneous, leading to challenges in formulating accurate models of sound propagation. In order to quantify acoustic responses in space and time, we perform experiments in a photoelastic granular material in which the internal stress pattern (in the form of force chains) is visible. We utilize two complementary methods, high-speed imaging and piezoelectric transduction, to provide particle-scale measurements of both the amplitude and speed of an acoustic wave in the near-field regime. We observe that the wave amplitude is on average largest within particles experiencing the largest forces, particularly in those chains radiating away from the source, with the force-dependence of this amplitude in qualitative agreement with a simple Hertzian-like model. In addition, we are able to directly observe transient force chains formed by the opening and closing of contacts during propagation which do not follow this trend. The speed of the leading edge of the pulse is consistent with predictions and experiments for one-dimensional chains. The slower speed of the peak response suggests that it contains waves which have traveled over multiple paths even in this near-field region. These effects highlight the importance of particle-scale behaviors in determining the acoustical properties of granular materials, and point to possibilities for characterizing force chain networks using acoustical techniques.

Phase Synchronization of Directly Coupled Boolean Chaos Oscillators, Myung Park, *University of Maryland / IREAP*
Synchronization phenomena has been extensively investigated in various applications including encrypted communication, ultra-wideband radio frequency sources, and short-range sensor networks. Among the different types of synchronization, identical synchronization is considered as the complete coincidence of states in coupled systems. A generalized synchronization for drive-response systems, is defined as the presence of a functional relation between the states of the drive and response systems. Finally, phase synchronization means phase locking in the drive and response systems, while the amplitudes of the coupled systems remain chaotic. In this work, we study phase synchronization of our previously studied Boolean chaotic oscillator, consisting of one ring oscillator, one XOR , and two delay buffers to compare with the experimental results. This Boolean chaos oscillator also has been modelled using the BSIM3 transistor model. We constructed a Boolean chaos oscillator using commercially available high-speed logic gates in a feedback loop to generate chaotic behaviors. The temporal evolution of the voltage at a point demonstrates a broad power spectrum extending to 1.5 GHz. In addition, bifurcations occur with the supply voltage. Previous Boolean chaos oscillators [1] have been studied using the Boolean delay equation by Ghil et al. [2]. Because physical components of logic gates consist of multiple transistors, BSIM3 transistor model [3] is more promising for an analog analysis of the system dynamics. The circuits are coupled with a resistor and measured at the same node in the two circuits. To quantify the coupling strength, a coupling coefficient K is defined as the inverse of resistance. To describe the phase synchronization, we used a Hilbert transform of an output voltage for quantifying the phases. For both simulation and experiment, the phase difference between circuits is calculated and measured. For weak coupling, a histogram of phase difference is uniformly distributed whereas the histogram of phase difference in strong coupling shows a relatively narrow peak. The standard deviation of the histogram is used as an indicator of how the dynamics of synchronization change in terms of the coupling strength.
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Algortithm for Planar 4-Body Problem Central Configurations with Given Masses, Eduardo Piña, *Universidad Autonoma Metropolitana*
A particular solution to the Four-Body problem in the plane is obtained from the elliptic motion of the four bodies keeping a central configuration. An algorithm to compute the six distances between particles of a planar Four-Body central configuration is presented according to the following schema. An orthocentric tetrahedron is computed as a function of given masses, it is rotated by two angles (to be tuned variables) around the center of mass until a direction orthogonal to the plane of configuration coincides with axis 3. The four coordinates of the vertices of the tetrahedron along this direction are identified with the weighted directed areas of the central configuration. The central configuration corresponding to these weighted directed areas is computed giving rise to four masses and corresponding distances. The given masses are compared with the computed ones. The two angles of the rotation are tuned until the given masses coincide with the computed. The corresponding distances of this last computation determine the central configuration.

Mixing properties of a granular monolayer, James Puckett, *North Carolina State University*
In a dense driven granular system, the particle dynamics are often quantified by the self-diffusion coefficient, but this measure discards topological information important for measuring mixing. The topological entropy, S_{braid}, has been used in fluid systems to measure the entanglement of particle spacetime trajectories (Thiffeault, PRL, 2005). We experimentally investigate the effect of boundary condition (constant pressure or constant volume) and inter-particle friction on the dynamics of a granular liquid. The bidisperse monolayer of hard disks rests on a low friction air table and is driven by bumpers on the perimeter. We track the trajectories of the particles and observe that the braid entropy is a well-defined quantity: the logarithm of the braiding factor grows linearly in time. Both the diffusion coefficient and S_{braid} decrease with either increasing volume fraction or confining pressure, and we examine the extent to which the braid entropy provides

additional information about the state of the system.

Cyclic simple shear in a two-dimensional granular system, Jie Ren, *Duke University*
We study the evolution of a 2D granular system consisting of frictional photo-elastic disks under large numbers of small-amplitude cyclic shear cycles. We are particularly interested in the reversibility of the system under cyclic shear. The experiments are carried out on a specially designed apparatus which can create quasi-static, nearly uniform simple shear. By using photo-elastic particles and a fluorescent labelling technique, we obtain information about displacement, rotation and contact forces for each particle following each small strain. We also obtain the system-level behaviour over many shear cycles. To better understand the nature of jamming, we have carried out shearing runs that explore various initial states which are initially unjammed, isotropically jammed or anisotropically jammed, and we compare the results for different initial states.

Nonlinear synchronization of the Polar Regions? climatic oscillations over the last ice age: A working hypothesis, José Rial, *UNC-Chapel Hill*
An important clue to understand global climate dynamics is the apparent connection between the climates of the Polar Regions revealed by ice core paleoclimate proxies of the last ice age, which confirm the existence of a temperature bipolar seesaw (Antarctica warms while Greenland cools) whose origin is still poorly understood. Using a heuristic low-dimensional climate model and an earth model of intermediate complexity to back it up, it is shown that the polar connection is likely caused by synchronization (frequency and phase locking) of the climate oscillations from the two poles. Polar synchronization appears analogous to Huygens?s classic problem describing the synchrony of two non-identical pendulum clocks coupled by weak elastic forces along the wall on which they hung. Here I assume that polar climate fluctuations can each be represented by a self-sustained nonlinear relaxation oscillator (Huygens's clock), each with its own natural frequency and feedbacks, influencing each other through dissipative coupling proportional to the temperature and heat storage gradients between north and south Atlantic ocean and atmosphere (the common wall). Synchronization of polar climate oscillations explains recent data from the southern ocean showing abrupt temperature change in anti-phase with Greenland's Dansgaard-Oeschger (DO) fluctuations, it explains Antarctica's temperature lead on abrupt warming episodes of the DO, and the linear dependence between the duration of stadial (cold) intervals in the north and peak temperature in the south. The synchronization model explains the bipolar climatic seesaw and makes two testable predictions: recordings of northern mean ocean temperature should exist that are in anti-phase to Antarctic ice core records, and southern temperature records should exist that are in anti-phase to Greenland's DO records. Though the former has yet to be found, evidence for the latter was recently obtained in the South Atlantic.

Effect of strength-interval relationship on cardiac rhythm dynamics in a one-dimensional mapping model, Caroline Ring, *Duke University*
Authors: Caroline L. Ring MS, David G. Schaeffer PhD, Wanda Krassowska Neu PhD
Cardiac muscle cells respond to electrical stimuli above a certain threshold strength by producing action potentials (APs), during which the cells contract. A cell's response to a train of stimuli applied at some constant pacing rate (basic cycle length, or BCL) may be characterized by the durations of the resulting train of action potentials (action potential duration, or APD). A regular APD response results in the normal, organized contraction of the heart to pump blood. An irregular or chaotic APD response can result in deadly cardiac arrhythmia. Therefore, the mechanisms by which irregular APD dynamics arise are of great interest. APD dynamics can be studied using a mapping model, in which APD is a function of one or more previous APDs. APD dynamics in mapping models are more easily analyzed than in detailed physiological AP models described by many ODEs. We consider a one-dimensional mapping model, in which APD is a function of one previous APD, and BCL is a parameter of the function: $\mathrm{APD}_{n+1} = F(\mathrm{APD}_n; \mathrm{BCL})$ At present, there are two routes to irregular dynamics (ID) in one-dimensional mapping models. First, ID arises from period-doubling bifurcations. The slope of F increases with decreasing BCL, causing APD behavior to move from period-1 to period-2 (alternans, 2:2) to period-4, and so on to chaos. Second, as BCL decreases, APD becomes shorter than the shortest APD at which the map function F is defined. This leads to phase-locking responses of captured and missed beats: an AP for every stimulus (1:1), for every two stimuli (2:1), every three stimuli

(3:1), and so on. The range of APDs over which F exists for a given BCL is determined by the strength-interval (S-I) curve. The S-I curve gives the relationship between S, the minimum stimulus strength necessary to elicit an AP, and BCL-APD, the interval before the next stimulus: S = G(BCL-APD_n) The map function F exists on the intervals of APD where the stimulus strength lies above the S-I curve, and does not exist elsewhere. If map iteration reaches an APD where F does not exist for a given BCL, then the beat is missed and the next APD will be governed by F for 2*BCL, until an APD is reached where either F for 2*BCL does not exist (in which case the next APD will be governed by F for 3*BCL), or F for BCL again exists (in which case the beat is captured). Depending on the position and stability of the fixed points of these map functions, and the boundaries of these functions, APD may aperiodically "jump" between map functions forever, producing sustained ID. Previous hypotheses hold that this mechanism can only cause ID if the S-I curve is triphasic, and the stimulus strength lies between the local minimum and local maximum of the S-I curve — giving rise to a gap in the map function F. Our work, however, shows that ID can be obtained in a one-dimensional mapping model without a gap in F (i.e. when the S-I curve is not triphasic). We have reproduced irregular dynamics (ID) in a simple, two-current mathematical model of the cardiac action potential. By asymptotic analysis, we have simplified the full model (consisting of two nonlinear ODEs) to a one-dimensional nonlinear map with BCL as a parameter. We considered three shapes of the S-I curve: monophasic, biphasic, and triphasic. We examined BCL between 150 ms and 1000 ms, and stimulus strengths between 0.1 and 0.3 (scaled voltage units). APD behavior was characterized over 1000 beats for each combination of S-I curve shape, BCL, and stimulus strength. Map iterations produced sustained ID for BCLs between 210 and 220 ms. For BCLs ranging from 150-200 ms, APD behavior moved from 6:2 to 3:1. For BCLs ranging from 230-1000 ms, behavior moved from 2:1 to 1:1. For the monophasic S-I curve, sustained ID was observed at BCL = 210-220 ms for all stimulus strengths. For biphasic and triphasic S-I curves, sustained ID was only observed at these BCLs at stimulus strengths above 0.15; for lower stimulus strengths, transient ID was observed for about 100 beats, resolving to 2:1 behavior. Analysis of the mapping model dynamics shows that the development of sustained ID depends not only on the stability of fixed points of the map, but also on the change in the extent of the map function F from beat to beat. The change in the extent of F arises because the S-I curve depends on the previous APD. Since F exists only where the chosen stimulus strength lies above the S-I curve, the extent of F changes depending on the previous APD. Our results suggest another possible mechanism for irregular APD dynamics under constant pacing. Our analysis of ID in a one-dimensional mapping model may elucidate underlying mechanisms of irregular cardiac rhythms observed in our experiments, and may inform the study of new methods of diagnosing or preventing cardiac arrhythmias.

Frequency-comb generation with an opto-electronic oscillator, David Rosin, *Technische Universität Berlin, Duke University*
Authors: David Rosin, Kristine E. Callan, Daniel J. Gauthier, Eckehard Schöll

We experimentally observe several pulsing and bursting solutions in a high-speed, time-delay opto-electronic oscillator [1], which is comprised of commercially available components.The pulses and bursts are spaced by submultiples of the time-delay of the feedback loop. We are especially interested in a solution with only one pulse per time delay. The regime in parameter space where the pulse train solution exists is mapped out experimentally and is compared to numerical simulations of the underlying mathematical model. We find a bifurcation between a pulsing solution with wide pulses, with a duration of 1 ns, and narrow pulses, with a duration of 350 ps. The related bifurcation threshold is measured in the parameter space. The pulse train with the narrowest pulses, with a duration of 180 ps, corresponds to a frequency comb which extends further than 8 GHz, the bandwidth of the oscilloscope used. We also measure the phase noise of the fundamental frequency of the comb for different time delays. Theoretically, we show that the system is likely to produce pulses because, for periodic solutions, it shows strong similarities to the generic FitzHugh-Nagumo model. The system could be used as an inexpensive frequency comb generator, which also makes it technologically attractive.

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Deformable self-propelled domain in a three-dimensional excitable reaction-diffusion system, Kyohei Shitara, *Kyoto University*

Our understanding of active matter has been advanced for the last few decades. Particularly, self-propelled objects have attracted considerable attention because these are related with various non-equilibrium phenomena. For example, there are lots of biological phenomena such as motion of bacteria, moving cells, dynamics of a school of swimming fish or a flock of flying birds and so on. Furthermore, a self-driven oil droplet has been observed experimentally [1]. Dynamics of a self-propelled domain in a reaction-diffusion system has been investigated by a numerical simulation [2]. There is, however, few theory considering the effect of deformation of self-propelled particles. Ohta and Ohkuma have proposed a model of self-propelled particles which deform when the propagating velocity is increased [3]. It has been shown that a single deformable self-propelled particle has a bifurcation from a straight motion to a rotating motion in two dimensions. Quite recently, we have derived, by a singular perturbation method, the set of time-evolution equations of a deformable self propelled domain starting from an excitable reaction diffusion system both in two and three dimensions [4]. The shape of domain propagating at a constant velocity has been determined. Solving this set of equations numerically in three dimensions, we have found a new bifurcation from a rotating motion to a helical motion caused by a biaxial deformation [5] and the parameter regime where the helical motion appears has been explored.

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Excitable Nodes on Random Networks: Structure and Dynamics, Thounaojam Umeshkanta Singh, *Jawaharlal Nehru University, New Delhi*

Authors: Th. Umeshkanta Singh, K. Manchanda, R. Ramaswamy, School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110 067, India, and A. Bose, School of Physical Sciences, Jawaharlal Nehru University and Department of Mathematical Sciences, New Jersey Institute of Technology, Newark, NJ 01702 USA

The generation of rhythmic activity in complex system arises from interaction between the components. We study the interplay of topology and dynamics of excitable nodes on random networks. Each node is a cellular automaton which can be active (positive integers), silent (zero), or refractory (negative integers), and dynamical evolution proceeds via a set of loading rules. In simple loading (SL), a silent node becomes active when it receives an input from atleast one of its active neighbors whereas in majority rule (MR), a majority of neighbors are required to be in active state for a silent node to become active. We address the question of whether a particular network design or motif confers dynamical advantage, and which other intrinsic properties of the node promote rhythmic activity. Closed pathways are necessary for propagation of activity with SL, while for MR, isolated minimal cycles are required. As a consequence, SL supports more dynamical activity than MR in random networks. In situation where the nodes have longer active duration relative to their refractory state, the presence of cycles is not required; instead a link between the nodes can support activity in the network.

Identification of delays and discontinuity points of unknown systems by using synchronization of chaos, Francesco Sorrentino, *University of Maryland at College Park and Universitá degli Studi di Napoli Parthenope*

I present an approach in which synchronization of chaos is used to address identification problems. The goal is to synchronize a receiver system whose parameters can be adaptively evolved to a sender chaotic system with a set of unknown parameters. By seeking synchronization between the sender and the receiver, the adaptive strategy is able to reconstruct the set of unknown parameters of the sender. I show the usefulness of this approach in identifying (i) the discontinuity points of systems described by piecewise equations and (ii) the delays of systems described by delay differential equations.

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Relation between Autonomous Boolean and ODE Models of a Gene Regulatory Network,

Mengyang Sun, *Duke University*
We present an autonomous Boolean network (ABN) model based on the ODE model of von Dassow et al [2000] for the Drosophila segment polarity gene regulatory network. The ABN model highlights timing and logic constraints that are hidden in ODE models. In the ABN model the binary output value of each node is governed by Boolean functions and update times are encoded in delay parameters associated with each link. Given the ODE network, we construct a corresponding ABN by adjusting the topology, logic functions and delay parameters. We show that this ABN can reproduce the stable segmentation pattern observed in experiments, and we derive the constraints satisfied by successful choices of time delay parameters.

Theory and experiment of fast non-deterministic random bit generation with on-chip chaos lasers, Satoshi Sunada, *NTT Communication Science Laboratories*
Random bit generation is important for many applications, such as cryptography, numerical computation, and stochastic modeling. In particular, fast generation of unpredictable truly random bit sequences is very important to achieve high security of communication systems. Recently, random bit generation using chaos in semiconductor lasers has been developed in order to obtain unpredictable truly random bit sequences extremely fast [1]. In this system, chaotic oscillation of high frequency above the order of GHz is produced from the lasers with optical delayed feedback. Random bit sequences are generated by sampling and converting the fast chaotic signals into binary signals at fast rates over one gigabit per second, much faster than any other physical random bit generator. While many experimental demonstrations of random bit generation with chaotic lasers have been reported [1-3], the role of chaos in generating random bits has not yet been studied theoretically. True random behaviors can never be obtained only from the chaotic dynamics subject to deterministic laws. It is important to elucidate the mechanism of the physical random bit generation with chaotic lasers and the origin of its intrinsic randomness. In this presentation, we theoretically show that non-deterministic random bits can be generated due to the combination of the mixing property of a chaotic laser system and microscopic noises. The origin of the randomness is microscopic quantum noises due to spontaneous emission. The mixing property of the chaotic laser system transforms microscopic noises to macroscopic random signals. The process of the transformation and the randomness of the generated bit sequences are numerically investigated by using standard chaotic semiconductor laser model equations (Lang-Kobayashi equations) with microscopic noises. On the basis of the theoretical and numerical considerations, we designed chaos laser devices suitable for fast random bit generation and fabricated the devices on a semiconductor chip with photonic integration technologies. We experimentally demonstrate that random bit sequences passed standard statistical test suites for randomness can be generated at fast rates up to 2 Gbps using the chaos laser devices.

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Blowout bifurcation and spatial mode excitation in the bubbling transition to turbulence, José Danilo Szezech, *Universidade de São Paulo*
The transition to turbulence (spatio-temporal chaos) in a wide class of spatially extended dynamical system is due to the loss of transversal stability of a chaotic attractor lying on a homogeneous manifold (in the Fourier phase space of the system), causing spatial mode excitation. Since the latter manifests as intermittent spikes this has been called a bubbling transition. We present numerical evidences that this transition occurs due to the so-called blowout bifurcation, whereby the attractor as a whole loses transversal stability and becomes a chaotic saddle. We used a nonlinear three-wave interacting model with spatial diffusion as an example of this transition.

Jamming of Granular Flow in a Two-Dimensional Hopper, Junyao Tang, *Duke University*
We seek an understanding of the physics of jamming in hopper flow, using high speed spatio-temporal

video data for photoelastic disks flowing through a two-dimensional hopper. We have found experimental support for the hypothesis that jamming events of granular flow in a hopper is approximately a Poisson process. The mean flow time between two consecutive jams increases rapidly while the hopper opening increases, but it is insensitive to changes of the hopper wall angle. Through particle tracking and photoelastic measurements, we measure stress field, velocity field and density field, as well as fluctuations of each during the flow. Current work focuses on combining these results to give further insights into the relation between mean flow properties and jamming and their dependence on hopper configuration. These data are part of an IFPRI-NSF Collaboratory for comparing physical data and simulations.

Avalanching and shear of vibrated granular/granular-fluid mixtures, Brian Utter, *James Madison University*
The behavior of dense granular materials can be characterized by the continuous forming and breaking of a strong force network resisting flow. This jamming/unjamming behavior is typical of a variety of systems and is influenced by factors such as grain packing fraction, applied shear stress, and the random kinetic energy of the particles. Statistical measures are desired to characterize the state of the system. We present experiments on shear strength of granular and granular-water mixtures under the influence of external vibrations, one parameter that leads to unjamming. We use low vibration (< 1g) and slow shear and measure avalanching statistics in a rotating drum and the torque required to move a stirrer through a sand/water mixture. We find that external vibration (i) increases granular strength at small vibrations in the dry system, (ii) removes history dependence (memory), and (iii)decreases shear strength at all accessible saturation levels in the sand-fluid system. Additionally, shear strength is found to be smallest for both dry and completely saturated mixtures. For moderate saturation levels, the variability of the data is small. Additional ongoing experiments are probing beyond G = 1 and exploring jamming and surface chemistry effects in the flow of granular/fluid mixtures.

Velocity Vector Field Pattern in a 2x2 game of Human Subject Experimental Economics Experiment, Zhijian Wang, *Zhejiang University*
Taking the detailed balance condition (H. Peythan Young 2005) or/and the time reversal transformation (Baiesi, Maes and Wynants 2009) into consideration, we present the Bertrand-Edgeworth-Shapley cycle (Cason, Friedman and Wagener 2005) in a two-dimensional 5×5 lattices space based on our data from laboratory experimental economics experiments. We have, total 96 subject attended, 12 independent sessions and in each session 4 Up-Down players and 4 Right-Left players play a 2×2 game with the payoff matrix of $[(5,0)(0,5);(0,5)(5,0)]$ in pairs over 300 periods under random matching protocol. We suggest that, a social Markov jumping in strategy space is a velocity vector, and then it can be measured. By analyzing our experimental data, we find that these vectors form a significant spiral vector field in the 5×5 lattices space. Filtering out the detailed balance (or called as traffics process by physicist), we get a clear dynamic pattern (Fig.3(b,c,d,e)). We also find a ring-mountainshaped distribution of the time anti-symmetric Markov jumping in the two-dimensional space (Fig.3(f)). Both algebra matrix analysis and geometrical presentation method reach the same result. These findings, together with the method, suggest considerable connections between evolutionary game theory and experimental economics.

The Effect of Network Structure on the Path to Synchronization in Large Systems of Coupled Oscillators, Matt Whiteway, *University of Oklahoma*
The Kuramoto Model has been used extensively as a tool for understanding the dynamics of large systems of oscillators that are either coupled globally, locally, or through a complex network. We are interested in the path that systems of networked oscillators take to global synchronization as the coupling strength between oscillators is increased. We employ the Kuramoto Model to study the effects of network size, degree distribution, and natural frequency distribution on the dynamics of these systems. A recent study has shown that small clusters of synchronized oscillators form before the entire system transitions to a state of global coherency. The main result from our work is that this local synchronization is largely independent of both the size and natural frequency distribution of the system, and is instead highly dependent on the average number of links per oscillator, becoming less prominent as this average increases.

Voltage interval mappings for activity transitions in neuron models for elliptic bursters, Jeremy Wojcik, *Georgia State University and Neuroscience*

Institute
We perform a thorough bifurcation analysis of a mathematical elliptic bursting model, using a computer-assisted reduction to equation-free, one-dimensional Poincaré mappings for a voltage interval. We examine the bifurcations that underlie the complex activity transitions between tonic spiking, bursting, mixed-mode oscillations as well as quiescence; in the Fitzhugh-Rinzel model and we compare our findings with two biologically relevant models for elliptic bursters; a bursting adaption of the classical Hodgkin-Huxley model, and a realistic Rubin-Terman model for the external segment of the Globus Pallidus. We illustrate the wealth of information that can be derived from continuous Poincaré mappings, both qualitatively and quantitatively, which cannot be found directly from discrete mappings generated from the flow.

A free energy simulation approach to the study of equilibrium modulated phases, Kai Zhang, *Duke University*
Spatially periodic patterns that result from equilibrium or out-of-equilibrium processes are observed in a variety of physical and chemical systems. While identifying pattern formation of nonequilibrium phenomena, such as Rayleigh-Bénard convection, usually involves directly solving for the nonlinear time evolution, equilibrium modulated phases, such as microphases in diblock copolymers, correspond to minimizing a Landau-Ginzburg free energy for a given morphology and periodicity. Any study of the microphase dynamical self-assembly thus requires a detailed understanding of the underlying equilibrium phase behavior. Microphase separation has been extensively studied by theoretical analysis, experiments, coarse-grained numerical optimizations and particle-based simulations. However, due to the high free energy barriers that separate the various phases, identifying the stable morphologies and periodicity in microphase-forming systems is difficult on the accessible experiment and simulation time scale. We develop a simulation methodology based on thermodynamic integration by which we can obtain the absolute free energy of different modulated phases. We adopt the method in a Monte Carlo simulation of two microphase-forming spin systems, i.e., the axial next-nearest-neighbor Ising (ANNNI) model and the Ising-Coulomb (IC) model. The accurate equilibrium phase diagram prediction in those systems demonstrates that our method successfully circumvents the long-existing problem of kinetic arrest in the study of equilibrium modulated phases.

Bistability and Oscillations in Fluid Networks, John Geddes, *Franklin W. Olin College of Engineering*
Fluid networks in which the resistance to flow depends on the fluid in a nonlinear fashion are quite common. Some examples include the flow of blood through the microcirculation, the flow of bubbles or droplets through microfluidic devices, or the flow of magma through a volcanic chamber. Over the last few years we have developed a general theory for such fluid networks which takes into account two main sources of nonlinearity: the dependence of the local resistance on the fluid, and the partition rule for the fluid at network nodes. We have demonstrated theoretically that bistability and oscillations are to be expected, and we have confirmed these predictions in experiments on several model systems. In this presentation we will describe the nonlinear dynamics of fluid networks, and present our latest experimental studies.

Nonlinear Dynamics and Methods of Investigation of Chaotic Time Series in the Brain, Nayoung Koh, *University of California, Irvine*
Wook Hee Koh, Department of Physics, Hanseo University, Seosan, Chungcheongnam-do, Korea, Nayoung Koh, Department of Anatomy and Neurobiology, University of California, Irvine, California, USA, Minjeong Koh, School of Social and Behavioral Sciences, Irvine Valley College, Irvine, California, USA
A complex biological system, such as the brain, cannot be fully understood in the context of physiology through the application of purely reductionistic methods due to the dynamical nature in its function based upon collective behavior as a whole rather than simply the sum of its individual components. Numerous investigators in neuroscience have demonstrated the importance and the necessity of the use of analytical tools, such as chaos theory, to explain the nonlinear phenomena of higher brain functions from information processing to perception and memory. The elementary processing units in the brain are neurons which are connected to each other in an intricate pattern. The neuronal signals consist of short electrical pulses, so-called action potentials or spikes. A chain of action potentials emitted by a single neuron is called a spike train which occurs at regular or irregular intervals. The form of the action potential does not carry any information. Rather, it

is the number and the timing of spikes that encode and transmit stimulus information. Therefore, it is essential to analyze in depth the time series of spike train in order to understand the properties of cortical networks and higher brain function. Here, we introduce the concepts of nonlinear dynamics underlying a spike train as well as the methods for time-series analysis, such as return maps and surrogate strategy. We also present simulation results obtained by using our numerical codes of spiking neuron models designed to examine the nonlinear properties of neuronal firing pattern.

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