Poster Session A

Friday Jan. 4, 7:30pm-9:30pm

A1 - Existence and Stability of Left-Handedness: an Evolutionary Model

Daniel Abrams, Mark J. Panaggio, *Northwestern University*.

An overwhelming majority of humans are right-handed. Numerous explanations for individual handedness have been proposed, but this population-level handedness remains puzzling. I will present a novel mathematical model and use it to test the idea that population-level hand preference represents a balance between selective costs and benefits arising from cooperation and competition in human evolutionary history. I will also present evidence of atypical handedness distributions among elite athletes, and show how our model can quantitatively account for these distributions within and across many professional sports. The model predicts strong lateralization for social species with limited combative interaction, and elucidates the absence of consistent population-level "pawedness" in many animal species.

A2 - Criticality of Forcing Directions on the Clustering, Fragmentation and Resilience of Grid Networks

Cheryl Abundo, E.F. Legara, C. Monterola, *University of the Philippines Diliman, IHPC, Agency for Science, Technology and Research, Singapore*.

We show that the resilience of a network to edge failure and system collapse is dependent not only on the magnitude of forces experienced by the network but also crucially on the network's interconnection pattern. In this work, the evolution of a grid network and an Erdös-Rényi network is modeled by taking into account the forces that exist between connected nodes. We find that for a grid network, the resulting fraction of disconnected edges follows a linear trend with a slope of 0.50. A grid network retains half of its edges, $f = 0.496 \pm 0.007$, when force sources are positioned randomly, but when nodes are arranged in order of force influence, the network totally collapses. However, for an Erdös-Rényi network, the system totally fragments regardless of the positioning of influential nodes. We further show that the time if it takes for the networks to reach its equilibrium network structure follows a power law relationship, regardless of node positioning and connectivity. Further, it can be changed by as much as 0.31 by only changing the forcing pattern.

A3 - Population Scale Physiologic Measurement, Dynamics and Prediction

David Albers, George Hripcsak, *Department of Biomedical Informatics, Columbia University*.

While humans are at some level similar biological machines, human physiologic dynamics have considerable variation, and these variations are often related to very practical observables. To resolve and understand this variation, we need two basic components. First, to resolve this variation we need to have a data source that has a diverse set of sources with different responses. Second, to understand the variation, we need a mechanistic means, often via a mechanistic physiologic model, to explain the variation. In this talk I will discuss various methodologies for deriving and explaining data-driven physiologic signals derived from population scale physiologic data and some of the results that these methodologies have generated. The particular results will be primarily related to endocrine (e.g., glucose/insulin) and neurophysiologic dynamics. The methodologies range from signal processing, information theory and nonlinear time series analysis to mechanistic physiologic modeling that hints at potential applications of data assimilation and control theory.

A4 - Explosive Percolation in Directed Networks

Diego Alcala[1], Katherine Sytwu[2], Shane Squires[2], Tom Antonsen[2], Michelle Girvan[2], Edward Ott[2], [1]*University of Northern Colorado,* [2]*University of Maryland*.

Complex networks arise in various areas of interest: power grids, gene regulation, information networks, etc. One important characteristic of complex networks is their ability to percolate; the sudden formation of a giant component that connects a macroscopic fraction of the total network. Past research has shown that if connections are competitively added in undirected complex networks, the formation of a giant connected component can be delayed, resulting in a first-order transition in the size of the giant connected component, known as explosive percolation. We generalize that concept onto directed networks which, like undirected networks, have an analogous giant strongly connected component. Since directed networks have directed connections, the giant strongly connected component can reach a giant component, called the giant out, which itself has no connections leading back to the giant strongly connected component. We show that the giant out component also undergoes explosive percolation, and compare our findings with the corresponding undirected case.

A5 - Complex Solitary Wave Dynamics in a Gain Loss Nonlinear Schrödinger Equation

Justin Q. Anderson, Rachel A. Ryan, Mingzhong Z. Wu, Lincoln D. Carr, *Colorado School Of Mines*.

The gain loss nonlinear Schrödinger equation (GLNLS) was proposed as a model for spin-wave envelope dynamics for nonlinear thin film magnetostatic active feedback rings and analogous driven damped physical systems. Bright soliton trains were spontaneously driven out of equilibrium and behaviors stable for tens of thousands of round trip times, O(100ms), were numerically identified. Six dimensional parameter space for the GLNLS in (1+1)D was explored and ten complex dynamical behaviors with experimentally accessible parameters were identified. Solution classes presented include symmetric and asymmetric N-peak interactions, dynamical pattern formation and complexly modulated soliton envelopes. Three dynamical behaviors are qualitatively matched to earlier works and seven new cases, five demonstrating long lifetimes, are presented.

A6 - Nonlinear Time-Reversal in a Wave Chaotic System

Matthew Frazier, Biniyam Taddese, Edward Ott, Thomas Antonsen, Steven Anlage, *University of Maryland*.

Time reversal mirrors are particularly simple to implement in wave chaotic systems and form the basis for a new class of sensors [1-3]. The sensors make explicit use of time-reversal invariance and spatial reciprocity in a wave chaotic system to sensitively measure the presence of small perturbations to the system. The underlying ray chaos increases the sensitivity to small perturbations throughout the volume explored by the waves. We extend our time-reversal mirror to include a discrete element with a nonlinear dynamical response [4]. The initially injected pulse interacts with the nonlinear element, generating new frequency components originating at the element. By selectively filtering for and applying the time-reversal mirror to the new frequency components, we focus a brief-in-time excitation only onto the nonlinear element, without knowledge of its location. Furthermore, we demonstrate a model which captures the essential features of our time-reversal mirror, modeling the wave-chaotic system as a network of transmission lines arranged as a star graph, with the discrete nonlinearity modeled as a diode terminating a particular line.

Work funded by the Intelligence Community Postdoctoral Research Fellowship Program and the Center for Nanophysics and Advanced Materials.

[1] B. T. Taddese, et al., Appl. Phys. Lett. 95, 114103 (2009).
[2] B. T. Taddese, et al., J. Appl. Phys. 108, 114911 (2010).
[3] S. M. Anlage, et al., Acta Physica Polonica A 112, 569 (2007).
[4] M. Frazier, et al., arXiv:1207.1667

A7 - Nonlinear Scale Interactions and Energy Pathways in the Ocean

Hussein Aluie, Matthew Hecht, Geoffrey Vallis, Kirk Bryan, Robert Ecke, Mathew Maltrud, and Beth Wingate, *Los Alamos National Laboratory*.

Large-scale currents and eddies pervade the ocean and play a prime role in the general circulation and climate. The coupling between scales ranging from $O(10^4)$ km down to $O(1)$ mm presents a major difficulty in understanding, modeling, and predicting oceanic circulation and mixing, where the energy budget is uncertain within a factor possibly as large as ten. Identifying the energy sources and sinks at various scales can reduce such uncertainty and yield insight into new parameterizations. To this end, we refine a novel coarse-graining framework to directly analyze the coupling between scales. The approach is very general, allows for probing the dynamics simultaneously in scale and in space, and is not restricted by usual assumptions of homogeneity or isotropy. We apply these tools to study the energy pathways from high-resolution ocean simulations using LANL's Parallel Ocean Program. We examine the extent to which the traditional paradigm for such pathways is valid at various locations such as in western boundary currents, near the equator, and in the deep ocean. We investigate the contribution of various nonlinear mechanisms to the transfer of energy across scales such as baroclinic and barotropic instabilities, barotropization, and Rossby wave generation.

A8 - Furling Dynamics of a Small Wind Turbine

Douglas Armstead, Wesley LaQuaglia, *Westminster College*.

We analyze the motion of a small model of a furling wind turbine in a wind tunnel. Furling is a means to passively protect wind turbines from high wind speeds using the dynamics of the device to turn it out of the wind. The desired behavior is steady-state, that is, the angle of the blade axis with the wind, Q, should be a single valued function of the wind speed, v. A subtle instability leads to oscillatory behavior at intermediate wind speeds. We characterize this transition by measuring both the time series of the power produced and Q as a function of v. The dynamics of this system are of interest because of the interplay between a relatively low dimensional turbine with high dimensional fluid dynamics, which leads to a system that is straight forward to measure but challenging to simulate and is practically relevant.

A9 - Parametric Instability in Waveguides with Axial Modulation of the Index of Refraction

Masoud Asadi-Zeydabadi, Randall Tagg, *University of Colorado Denver*.

Wave propagation in the geometrical optics limit is described by ray trajectories that obey Hamiltonian dynamics. Rays follow simple sinusoidal paths in waveguides where the square of the index of refraction varies quadratically with a transverse coordinate. However, modulation of the index of refraction in the axial direction causes a parametric instability of the ray traveling straight down the waveguide axis. The dependence of this instability on governing parameters is important for understanding the complex dynamics, including chaotic propagation, of other rays in the waveguide. A wide range of physical conditions is reducible to a two-parameter problem and linear analysis identifies instability tongues in this two-parameter space. One potential application is to light propagation in quasi-ordered system, including microoptic arrays and biological tissues.

A10 - The Complexity of Joint Processes and Channels

Nix Barnett, James P. Crutchfield, *University of California Davis*.

Entropy rate and excess entropy are information-theoretic measures of a stochastic process' irreducible randomness and apparent memory, respectively. The statistical complexity quantifies the actual memory required to predict or simulate a process. We examine how these quantities are modified when a process is transmitted through a communication channel and how coupled process quantities are related. In short, we extend the notions of entropy rate, excess entropy, and statistical complexity to communication channels and joint processes.

We first decompose a joint process' "joint entropy rate" into mutual and conditional entropy rates. When one process is the result of transmitting another process through a communication channel, this decomposition gives well defined bounds on the irreducible randomness lost, transmitted, and introduced by the channel.

We next decompose a joint process' "joint excess entropy" into nine components that measure the apparent memory lost, transmitted, and introduced by a channel. We demonstrate that synergistic memory arises from coupling that is not present in either process alone and provide information-theoretic interpretations of properties such as feedback and acausality.

Finally, we relate these measures to the statistical complexities of individual processes, joint processes, and communication channels. We show that these different statistical complexities bound various information-measure subsets of the joint excess entropy. This establishes that different forms of intrinsic "model overhead" are required to predict and simulate a joint process or communication channel.

A11 - Analysis of Fluid Systems from the Optical Flow-Approximate Vector Fields

Ranil Basnayake, Erik Bollt, *Clarkson University*.

Analysis of fluid systems such as the ocean and atmosphere is important topics in current research. To analyze global dynamics of such systems, such as coherent pairs and transport barriers, the vector fields of the systems are required. In the absence of a prior model, multi-time step optical flow technique can be employed on remote data to determine the vector fields. In this work, the transport barriers for the Jupiter's atmospheric data are explained.

A12 - Periodicity, Chaos and Oscillations in Some Planar Monotone Discrete Dynamical Systems with Negative Feedback

Sukanya Basu, *Central Michigan University*.

Oscillatory dynamics occur in many real-life applications such as, for example, thermostats in control systems and circadian rhythms in gene regulatory networks. One way to better understand this type of oscillatory dynamics is to study mathematical models involving discrete dynamical systems with negative feedback interconnections. In this talk, I will discuss the oscillatory behavior of orbits of order-reversing planar monotone maps which are associated in a natural way to planar discrete dynamical systems with negative feedback. Among other things, I will give some general yet simple geometrical criteria to determine when orbits of such maps show oscillatory stability in the form of periodicity and when they exhibit oscillatory instability in the form of chaos.

A13 - Intervention-Based Stochastic Disease Eradication

Lora Billings[1], Luis Mier-y-Teran-Romero[2], Brandon Lindley[3], Ira Schwartz[3], [1]*Montclair State University,* [2]*Johns Hopkins Bloomberg School of Public Health,* [3]*US Naval Research Laboratory*.

Disease control is of paramount importance in public health with infectious disease extinction as the ultimate goal. Although diseases may go extinct due to random loss of effective contacts where the infection is transmitted to new susceptible individuals, the time to extinction in the absence of control may be prohibitively long. Thus intervention controls, such as vaccination of susceptible individuals and/or treatment of infectives, are typically based on a deterministic schedule, such as periodically vaccinating susceptible children based on school calendars. In reality, however, such policies are administered as a random process, while still possessing a mean period. Here, we consider the effect of randomly distributed intervention as disease control on large finite populations. We show explicitly how intervention control, based on mean period and treatment fraction, modulates the average extinction times as a function of population size and the speed of infection. In particular, our results show an exponential improvement in extinction times even though the controls are implemented using a random Poisson distribution. Finally, we discover those parameter regimes where random treatment yields an exponential improvement in extinction times over the application of strictly periodic intervention. The implication of our results is discussed in light of the availability of limited resources for control.

A14 - How to Determine if the Cerebral Cortex Operates near Criticality

Doug Bohlman, Woodrow L. Shew, *University of Arkansas*.

Recent experiments suggest that the cerebral cortex operates in a dynamical regime near the critical point of a phase transition. The confirmation of this hypothesis would not only advance basic physiology of the brain, but also could explain how certain aspects of information processing are optimized, which is expected near criticality. However, determining whether the cortex is critical based on experimental data is challenging and some controversy surrounds typical approaches, such as neuronal avalanche size distributions. Here we introduce a new way to test for criticality, called a stability curve, which can be computed based on a single experimental dataset, e.g. the spike times recorded from a population of neurons over a period of 30 minutes. The stability curve quantifies the tendency for the population spike rate to increase or decrease as a function of the current spike rate. Importantly, our test accounts for the biggest constraint facing an experimentalist - that is, measurements are limited to a tiny subset of the full network of neurons. We developed this test using a network model of cortical neurons. Our model is closely related to directed percolation and branching processes. Action potentials propagate through the network probabilistically in discrete time steps, with the dynamics of the propagation determined by a competition between excitatory and inhibitory neurons. We generate stability curves based on model dynamics both near criticality and perturbed away from criticality (by altering the balance of excitation and inhibition) which provides concrete predictions for experiments.

A15 - Effects of Unresolved Turbulence on the Atmospheric Lagrangian Coherent Structures

Amir Ebrahim Bozorg Magham, Shane D. Ross, *Virginia Tech*.

In an autonomous system the invariant manifolds control the overall configuration of the phase space. Similarly, the hyperbolic Lagrangian coherent structures (LCSs) are the pathways that control the global configuration of the flow maps in the extended time varying phase spaces. These features are also the boundaries of the coherent structures since they are locally the strongest repelling or attracting material surfaces.

Studying these features in the rich dynamical context of atmospheric systems provides an understanding of transport and mixing phenomena especially in case of passive tracers. When atmospheric data are considered for calculation of the flow maps and the associated LCS features, one must be aware of the uncertainties and the limitations imposed on the precision of the results due to the coarse spatiotemporal resolutions of the data, where sub-grid scales phenomena such as local eddies or saddle points cannot be captured by interpolation methods. The motivation of this research is studying more realistic conditions and considering the effects of unresolved turbulence on the LCS features (this concern can be extended to any general case of time varying vector fields with drift and turbulent diffusion terms where the latter one could be a stochastic function of position, drift term and time).

Results show that considering the stochastic turbulent term could cause different qualitative changes on the finite time Lyapunov exponent (FTLE) fields and the associated LCSs. We summarize these qualitative changes into some major categories. In addition, including the turbulent unresolved velocity extends the definition of end (source) point position to the more general concept of probabilistic destination (source) area. Among the applications of this new observation is the identification of the possible origins of the sampled particles (such as spores or plumes particles) at a fixed location.

A16 - Detecting the Position and Strength of Attenuating Elements in a Small Network

Kristine Callan, Damien Rontani and Daniel J. Gauthier, *Duke University*.

Inferring network properties from the dynamics of the nodes in a network is both a challenging task and of growing importance for applied network science. A subset of this broad question is: how do we determine changes in coupling strengths between the elements (link weights) in a fixed network topology? We propose a method to simultaneously determine (1) which link is affected and (2) by how much when one of the coupling strengths in a small network of unsynchronized dynamical nodes is altered. After proper calibration, realizing this method involves only measurements of the dynamical features of a single node, such as the maximum and minimum signal amplitudes or time-delay signatures (peaks) in the signals autocorrelation function. We have also investigated ways to decrease the uncertainty in detecting both the position and strength of the attenuating element. We find that a node has enhanced sensing performance when it has: self-feedback, chaotic (rather than stochastic) dynamics, and parameter mismatch with respect to the other nodes in the network. We demonstrate experimentally our method using a network of optoelectronic oscillators (OEOs) operating in a high-speed and broadband chaotic regime [1]. We plan to extend this method to the design of an intrusion detection system, where several OEOs are spread around a scene and wirelessly coupled via antennas. The ultra-wide-band signals emitted by the nodes can pass through building materials with little attenuation, but would be strongly attenuated by a person who enters the path between two nodes. We expect that by monitoring the dynamics of one or more of the OEOs our method would be able to determine both the presence and approximate location of the intruder.

[1] K. E. Callan, et al., Phys. Rev. Lett. 104, 113901 (2010).

A17 - Synchronizing Frequency Selective Maps

Thomas Carroll, *US Naval Research Laboratory*.

The sensitivity of chaotic synchronization to noise has limited its practical application. If the interference is a narrow band signal, I show that it is possible to design a self-synchronizing chaotic map which avoids the interference frequency band. Avoiding the noise frequency completely is one way to synchronize chaotic systems when noise is present. This strategy for avoiding noise is motivated by recent work in cognitive radio, where the radio adapts itself to avoid noise frequencies.

A18 - On the Inverse Eigenvalue Problem by using the Kolmogorov-Sinai Entropy

Paul Cotae, *The University of the District of Columbia*.

The notion of the Kolmogorov-Sinai entropy was first studied by Kolmogorov in 1958 on the problems arising from information theory and dimension of functional spaces, that measures the uncertainty of the dynamical systems. We focus on the maximization of the mutual Kolgomorov-Sinai entropy $H(X,Y)$ of a known sequence X given a process Y. We will investigate the conditions when the mutual information $I(X,Y)$ derived by Shannon is equivalent to one defined by Kolgomorov and Sinai. We give an eigenvalue characterization of two processes which are diagonally equivalent to a Gaussian one. By using the inverse eigenvalue problem algorithms developed in the past we develop an algorithm to obtain the upper bound of the mutual Kolgomorov-Sinai entropy $H(X,Y)$. Mathematical formalism is illustrated with numerical examples.

A19 - On the Separation of Nearby Trajectories in Elliptical Stadia

Flavio M. de Aguiar, T. A. de P. Lima, *Universidade Federal de Pernambuco, Brasil*.

A stadium is a plane region comprised of two half-circles or two half-ellipses that bracket a rectangular sector of width $2h$ and height $2b$, where $b = 1$ is the radius of the circle or the minor axis of the ellipse. The circular or Bunimovich stadium exhibits the K-property for any arbitrarily small h. Here we focus on elliptical stadia with half major axis a in the interval $[1, 1.08]$. In this case, the corresponding billiards are surely chaotic if $h > c(a) = 2a^2\sqrt{a^2-1}$, [1] and exhibit a mixed phase if $h < h_0(a) = \sqrt{a^2-1}$ [2]. Whether or not there is a lower bound for chaos between these two curves is still an open problem. Numerical evidences indicate that if it exists it must be close to h_0. Here, for a given a, we have numerically calculated the mean separation d of nearby trajectories as a function of h in the vicinity of h_0. Let $s = \langle \log d \rangle$ be a peculiar time average that takes into account both the initial transient and the steady state regions up to some discrete time $T \sim 100$. We will present numerical evidences that $c = h(ds/dh)$ exhibits a pronounced peak at $h = h_0$, bearing resemblance to the lambda transition of the heat capacity of liquid ^{4}He as a function of the temperature at saturated vapor pressure. The mixed phase space for $h < h_0$ sets further the thermodynamic analogy with the two-fluid model, the irregular portion of the billiard phase space playing the role of the normal fluid component, and the regular one playing the role of the zero-entropy superfluid component.

[1] E. Canale and R. Markarian, Anales IEEE, Segundo Seminario de Informatica en el Uruguay, 71 (1991).

[2] E. Canale, R. Markarian, S.O. Kamphorst, and S.P. de Carvalho, The Erwin Schroedinger International Institute for Mathematical Physics, preprint 444 (1997).

A20 - Classical and Quantum Properties of Irrational Triangular Billiards

Flavio M. de Aguiar, T. A. de P. Lima, S. Rodríguez-Pérez, *Universidade Federal de Pernambuco, Brasil*.

Classical billiards in polygons are not chaotic, yet there are numerical evidences they might be ergodic. Here we use numerical and microwave techniques to investigate a number of particle and wave features in triangles whose sides are consecutive integers $(N, N+1, N+2)$. As recently demonstrated [1], all angles in a triangle belonging to this one-parameter family are irrational with π if $3 < N < \infty$. For the classical dynamics, we calculate the relative measure $r(t)$ of the occupied cells in a discretized surface of section as a function of the discrete time t, as well as position correlation functions, for varying N. Results are compared with the ones from the universal random model (RM) [2]. For small N, the calculated $r(t)$ is very close to the analytic result of the RM, and the correlation functions decay with an exponent close to -1. A slow departure from the thus characterized ergodicity is observed for $N > 20$. For the quantum dynamics, we numerically solve the Schrödinger equation with a boundary method. Short range (nearest neighbor spacing distribution) and long range (Dyson-Metha) statistics are calculated for the first $145,000$ energy eigenvalues beyond the first $5,000$ ones in the unfolded spectra. A departure from Random Matrix Theory is observed for $N > 20$, so that intermediate statistics are observed when the classical geometry is not strongly mixing. Scars were searched and not found in high-lying wavefunctions for $N < 20$, in qualitative agreement with the so called quantum unique ergodicity. Ghosts of classical periodic orbits could be found for quasidoublets which appear in the spectra for $N > 50$. These results fill a gap in the classical-quantum correspondence in regards to the ergodic hierarchy.

[1] F.M. de Aguiar, Phys. Rev. E 77, 036201 (2008).

[2] M. Robnik, J. Dobnikar, A. Rapisarda, T. Prosen, and M. Petkovsek J. Phys. A: Math. Gen. 30, L803 (1997); G. Casati and T. Prosen, Phys. Rev. Lett. 83, 4729 (1999).

A21 - A New Method for Computing Lyapunov Exponents for the Chaotic Bouncing Ball

Joseph Dinius, Ricardo Sanfelice, Joceline Lega, *University of Arizona*.

A new method is presented for computing the Lyapunov exponents of the chaotic bouncing ball. The method is developed and compared to previous numerical methods. Limitations of the previous method, along with how the new method addresses these limitations, is discussed. Results are presented verifying the proposed method, demonstrating the suitability of the approach for a wider class of hybrid dynamical systems.

A22 - Still Water: Dead Zones and Collimated Ejecta from the Impact of Granular Jets

Jake Ellowitz, Herve Turlier, Nicholas Guttenberg, Wendy W. Zhang, Sidney R. Nagel, *University of Chicago*.

Children learn that liquids are an intermediate state of matter: like gases, they flow easily but, like solids, they exist in a condensed state due to inter-particle attractions. In graduate school they may be taught that liquids can be simulated without attractions if the particle density is kept high by confinement. However, even without attractions or confinement, non-cohesive particles can behave like a liquid: when a high-density jet of grains hits a target it ejects particles in a thin sheet similar to the water bells created by liquid-jet impact. Our experiments, simulations and continuum modeling show that such ejecta sheets are generic and independent of the jet's internal kinematic features and the target shape. We show that this insensitivity arises because, surprisingly, the highly dissipative dense granular jet impact is controlled by the limit of perfect fluid flow. In contrast with the expectation that scattering provides sufficient information to reconstruct the internal state, the macroscopic observables, e.g., thin-sheet ejection angle, give little information about the jet dynamics when the density is high.

A23 - Camassa-Holm Equations and Vortexons for Axisymmetric Pipe Flows

Francesco Fedele[1], Denys Dutykh[2], [1]*Georgia Institute of Technology,* [2]*University College Dublin & Universite de Savoie*.

We present a study of the nonlinear dynamics of an axisymmetric disturbance to the laminar state in non-rotating Poiseuille pipe flows. In particular, we show that the associated Navier-Stokes equations can be reduced to a set of coupled Camassa-Holm type equations. These support inviscid and smooth localized travelling waves, which are numerically computed using the Petviashvili method. In physical space they correspond to localized toroidal vortices that concentrate near the pipe boundaries (wall vortexons) or wrap around the pipe axis (centre vortexons) in agreement with the analytical soliton solutions derived by Fedele (2012) for small and long- wave disturbances. Inviscid singular vortexons with discontinuous radial velocities are also numerically discovered as associated to special traveling waves with a wedge-type singularity, viz. peakons. Their existence is confirmed by an analytical solution of exponentially-shaped peakons that is obtained for the particular case of the uncoupled Camassa-Holm equations. The evolution of a perturbation is also investigated using an accurate Fourier-type spectral scheme. We observe that an initial vortical patch splits into a centre vortexon radiating vorticity in the form of wall vortexons. These can under go further splitting before viscosity dissipate them, leading to a slug of centre vortexons. The splitting process originates from a radial flux of azimuthal vorticity from the wall to the pipe axis in agreement with Eyink (2008). The inviscid and smooth vortexon is similar to the nonlinear neutral structures derived by Walton (2011) and it may be a precursor to puffs and slugs observed at transition, since most likely it is unstable to non-axisymmetric disturbances.

A24 - The Cloud-Rain System as a Set of Coupled Oscillators

Graham Feingold, Ilan Koren, *NOAA Earth System Research Laboratory*.

Shallow marine clouds appear in two formations - open cells that are weakly reflective and closed cells that are more reflective and hence more effective at cooling the climate system. Satellite data reveal that precipitating open cells oscillate, forming and disappearing with a periodicity of 3 hours. The emergent behaviour of these cells has recently been modeled using a set of coupled non-linear differential equations akin to the predator-prey model, with rain acting as the predator and cloud water, the prey. In this presentation we apply the same equations to individual elements of the cloud system. Each cloud element is an oscillator with a lifecycle of growth, decay, and regeneration. The cloud elements are coupled to one-another via the air motions associated with individual cloud growth/decay. We show how the coupling strength determines the level of organization of the cloud system, and compare the results to satellite observations and detailed large eddy simulation.

A25 - Critical Asymmetric Tori in the Multiharmonic Standard Map

Adam Fox, James Meiss, *University of Colorado at Boulder*.

Symplectic maps naturally arise from the study of Hamiltonian dynamics and have therefore been used in the analysis of a wide variety of systems, including particle accelerators, orbital dynamics, and the motion of billiards. Chirikov's standard map, describing the motion of a kicked rotor, is perhaps the best known and most closely studied example. Much of this study has focused on the existence and robustness of the maps' invariant rotational tori. These tori are of particular importance because they form a boundary to transport in the system. In 1979 John Greene developed a method to determine if a torus with a given frequency exists by studying the nearby periodic orbits. Efficient computation of these periodic orbits relies on symmetries in the map. If the rotor is forced with a function that is neither even nor odd these symmetries are destroyed. I will present an alternative method to determine if a torus with given frequency exists. This method uses a quasi-Newton scheme to numerically compute an embedding for the torus. The blow-up of the Sobolev Norm of this embedding can then be used to predict criticality. I apply this technique to study the multiharmonic standard map.

A26 - Blocking a Wave: Band Gap and Localization in the Vibrations of a Crevassed Ice Shelf

Julian Freed-Brown, Wendy Zhang[1], Arash Nowbahar[1], Jason Amundson[2] and Douglas MacAyeal[1], [1]*University of Chicago,* [2]*University of Alaska Southeast*.

Motivated by the sudden collapse of the Larson B ice shelf in Antarctica (2002), we assess how the propagation of high-frequency elastic-flexural waves through an ice shelf is modified by the presence of crevasses. A spatially periodic crevasse distribution introduces "band gaps", frequency ranges over which no normal modes exist. Intriguingly, an ice shelf 50 km across and 300 m thick supporting crevasses spaced 500 m apart has a first band gap around 0.3 Hz, a value relevant for ocean-wave/ice-shelf interactions. Disturbances to the shelf edge at this frequency are reflected back into the ocean. Disorder insulates the shelf further by localizing the normal modes at the band gap edges.

A27 - Optimal Species Dispersal in the Presence of Ecological and Evolutionary Costs

Theodore Galanthay, Samuel M. Flaxman, *University of Colorado at Boulder*.

Natural selection is an evolutionary mechanism that strongly affects species diversity. Classical ecological theory states that in a homogeneous environment, organisms with advantageous heritable traits will outcompete similar organisms lacking those traits. However, at suitable spatial scales environments are heterogeneous, and metapopulation models have shown that competitively inferior species can survive as long as they can disperse better than their competition. We seek to discover what form these optimal dispersal strategies might take. Treating dispersal strategies as a heritable trait, we analyze a simple single-species ordinary differential equation model describing theoretical movement between two different habitats. Using a combination of analytical and numerical methods, we identify evolutionarily singular dispersal strategies and show that they are evolutionarily and convergence stable. We incorporate two different types of costs, one ecological and the other evolutionary, and describe how these costs affect the optimal strategies.

A28 - Patterns and Oscillations in Reaction-Diffusion Systems with Intrinsic Fluctuations

Michael Giver, Daniel Goldstein, Bulbul Chakraborty, *Brandeis University*.

Intrinsic or demographic noise has been shown to play an important role in the dynamics of a variety of systems including predator-prey populations, biochemical reactions within cells, and oscillatory chemical reaction systems, and is known to give rise to oscillations and pattern formation well outside the parameter range predicted by standard mean-field analysis. Initially motivated by an experimental model of cells and tissues where the cells are represented by chemical reagents isolated in emulsion droplets, we study the stochastic Brusselator, a simple activator-inhibitor chemical reaction model. Our work extends the results of recent studies on the zero and one dimensional systems with the ultimate goals of understanding the role of noise in spatially structured systems and engineering novel patterns and attractors induced by fluctuations. In the zero dimensional system, we observe a noise induced switching between small and large amplitude oscillations when a separation of time scales is present, while the spatially extended system displays a similar switching between a stationary Turing pattern and uniform oscillations.

A29 - Solitons in Armchair and Zigzag Geometries in the Nonlinear Dirac Equation

Laith Haddad[1], Lincoln D. Carr[1,2], [1]*Colorado School of Mines,* [2]*Universität Heidelberg*.

We present solitons which solve the one-dimensional (1D) zigzag and armchair nonlinear Dirac equation (NLDE) for a Bose-Einstein condensate (BEC) in a honeycomb optical lattice [1]. The two types of NLDEs correspond to the two independent directions in analogy to the narrowest of graphene nanoribbons. We analyze the solution space of the 1D NLDE by finding fixed points, delineating the various regions in solution space, and through a conservation equation which we obtain as a first integral of the NLDE. For both the zigzag and armchair geometries we obtain soliton solutions using five different methods: by direct integration; through the conservation equation; by parametric transformation; a series expansion; and by the method of numerical shooting. We interpret our solitons as domain walls in 1D which separate distinct regions of pseudospin-$1/2$ with $S_z = \pm 1/2$, where the domain wall is topologically protected. By solving the relativistic linear stability equations (RLSE) we obtain the low-energy spectrum for excitations in the bulk region far from the soliton core and for bound states in the core and find that excitations occur as transverse and quadrupole pseudospin waves, and as a Nambu-Goldstone mode. For a BEC of $^{87}\mathrm{Rb}$ atoms, we find that our soliton solutions are stable on time scales relevant to experiments [2].

[1] L. H. Haddad, K. M. O'Hara, and Lincoln D. Carr. The nonlinear Dirac equation: Relativistic vortices and experimental realization in Bose-Einstein condensates. Phys. Rev. Lett., (2012), arXiv:1210.2114, under review.
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A30 - Three Dimensional Imaging of Slow Cyclic Shear-Driven Segregation

Matt Harrington[1], Joost Weijs[2], Wolfgang Losert[1], [1]*University of Maryland,* [2]*University of Twente*.

Heterogeneous mixtures of granular materials have a tendency to segregate by size under various disturbances, such as shear and gravity. While several models and approaches have been proposed, there is still much to learn about the mechanisms of shear-induced segregation, particularly for slowly driven dense systems. We have performed experiments on a three dimensional bidisperse mixture in a split-bottom geometry, under both steady and oscillatory shear. The pile continuously undergoes segregation described by the Brazil Nut Effect under steady shear, where large particles occupy the top of the pile. However, we find that the cyclically shear-driven system either remains mixed or segregates slowly, depending on shear amplitude. Using the Refractive Index Matched Scanning imaging technique, we characterize the segregating and non-segregating regimes by determining local reversibility with respect to space and structure, as well as visualization of the subsequent secondary flow profiles.

A31 - Engineered Gene Circuits: From Oscillators to Synchronized Clocks and Biopixels

Jeff Hasty, *University of California, San Diego*.

Synthetic biology can be broadly parsed into the top-down synthesis of genomes and the bottom-up engineering of relatively small genetic circuits. In the genetic circuits arena, toggle switches and oscillators have progressed into triggers, counters and synchronized clocks. Sensors have arisen as a major focus in the context of biotechnology, while oscillators have provided insights into the basic-science functionality of cyclic regulatory processes. A common theme is the concurrent development of mathematical modeling that can be used for experimental design and characterization, as in physics and the engineering disciplines. In this talk, I will describe the development of genetic oscillators over increasingly longer length scales. I will first describe an engineered intracellular oscillator that is fast, robust, and persistent, with tunable oscillatory periods as fast as 13 minutes. Experiments show remarkable robustness and persistence of oscillations in the designed circuit;

almost every cell exhibits large-amplitude fluorescence oscillations throughout each experiment. Computational modeling reveals that the key design principle for constructing a robust oscillator is a small time delay in the negative feedback loop, which can mechanistically arise from the cascade of cellular processes involved in forming a functional transcription factor. I will then describe an engineered network with intercellular coupling that is capable of generating synchronized oscillations in a growing population of cells. Microfluidic devices tailored for cellular populations at differing length scales are used to demonstrate collective synchronization properties along with spatiotemporal waves occurring on millimeter scales. While quorum sensing proves to be a promising design strategy for reducing variability through coordination across a cellular population, the length scales are limited by the diffusion time of the small molecule governing the intercellular communication. I will conclude with our recent progress in engineering the synchronization of thousands of oscillating colony "biopixels" over centimeter length scales through the use of redox signaling that is mediated by hydrogen peroxide vapor. We have used the redox communication to construct a frequency modulated biosensor by coupling the synchronized oscillators to the output of an arsenic sensitive promoter that modulates the frequency of colony-level oscillations due to quorum sensing.

A32 - Dynamic Localization of an Interacting Wavepacket in an Anharmonic Potential

Mark Herrera[1], Thomas M. Antonsen[1], Edward Ott[1], Shmuel Fishman[2], [1]*University of Maryland,* [2]*Technion-Israel Institute of Technology*.

We investigate the effect of anharmonicity and interactions on the dynamics of an initially Gaussian wavepacket in a weakly anharmonic potential. We note that depending on the values of interaction strength and anharmonicity, the quantum state can be either localized or delocalized in the potential. We formulate a model of this phenomenon in terms of a classical phase space and compare it to quantum simulations done for as a self consistent potential given by the Gross-Pitaevskii Equation.

A33 - Nonlinear Mode Decomposition of Oscillatory Time-Varying Dynamics

Dmytro Iatsenko, Aneta Stefanovska and Peter V. E. McClintock, *Department of Physics, Lancaster University*.

The identification and characterisation of dynamical systems often depends on the analysis of the signals that they generate. Here, we present Nonlinear Mode Decomposition (NMD), a new adaptive decomposition tool for signal analysis [1,2] based on the synchrosqueezed wavelet transform (SWT). It decomposes a signal into its nonlinear modes, i.e. into its full oscillatory components, including all harmonics. The NMD procedure consists of four parts, each of which is a useful technique in its own right: (i) accurate adaptive extraction of the instantaneous frequency of a mode; (ii) identification of possible harmonics; (iii) distinguishing the true harmonics; and (iv) reconstruction of the full nonlinear modes. We demonstrate the qualitative and quantitative superiority of NMD over the commonly-used decomposition methods such as empirical mode decomposition (EMD) and ensemble empirical mode decomposition (EEMD), and we show that NMD is noise-robust. We illustrate its application to a simulated signal and to a human EEG recording, obtaining excellent results in both cases. We point out that NMD is likely to be applicable and useful in many different areas of research. Thus, it can be used for the innumerable cases to which (E)EMD has been applied. By providing for reconstruction of the full nonlinear modes, it promises deeper insights into the underlying phenomena. Moreover, its extreme noise-robustness and other possible uses give it a wider range of applicability than (E)EMD and other decomposition methods. In particular, it can be applied to almost all multicomponent signals of the kind that are ubiquitous in the life sciences, climate studies and astrophysics, and it seems likely to become a new standard for signal decomposition.

[1] For preprint see http://arxiv.org/abs/1207.5567

[2] The MATLAB codes necessary for running NMD are freely available at http://www.physics.lancs.ac.uk/research/nbmphysics/diats/nmd/

A34 - Static Wealth Distribution on Complex Networks

Takashi Ichinomiya, *Graduate School of Medicine, Gifu University*.

We study the static probability distribution function (PDF) of Bouchaud-Mezard model, which was proposed to explain the Pareto's distribution in wealth, on complex network. Assuming the spatial and temporal correlation of wealth to be small, we derive the self-consistent equation which gives static PDF. We test the results of our theory by comparing them with the those of numerical simulations on several network models. We find good agreement between the results of our theory and those of simulations, except for the case of Watts-Strogatz network with small rewiring rate.

A35 - Effects of Traumatic Brain Injury upon the Architecture and Nonlinear Dynamics of Cortical Networks

Andrei Irimia, S.Y. Matthew Goh, Micah C. Chambers, Paul M. Vespa, Jeffry R. Alger, David A. Hovda, Arthur W. Toga, Ron Kikinis, John D. Van Horn, *University of California, Los Angeles*.

Introduction. Brain networks can be conceptualized as complex biological systems with components that exhibit nonlinear interactions and give rise to emergent behavior. Thus far, cortical network dynamics have been primarily used to study the healthy brain, and insufficient attention has been dedicated to the impact of brain lesions upon cortical network architecture. Moreover, the dynamic effects of cortical reorganization upon brain connectivity are inadequately understood. Motivation and purpose. Here, the effects of traumatic brain injury (TBI) upon the brain are explored using a computational framework whereby targeted brain lesions are simulated and their effects upon metrics of cortical architecture and dynamics are assessed. The purpose of this investigation is to explore the relationship between pathology-related changes in cortical architecture and dynamics, on the one hand, and clinical correlates of TBI patient evolution and outcome, on the other hand. Our purpose is to develop novel methodologies that can inform treatment decisions and thereby contribute to clinical outcome improvement. Methods. A technique for the representation of pathology effects upon brain connectivity is introduced and validated on a data set consisting of cortical networks extracted from 110 healthy human adults using magnetic resonance and diffusion tensor imaging (MRI and DTI, respectively). Contiguous cortical lesions are simulated in each of these patients at homogeneously distributed locations throughout the brain, and the effects of the former upon brain architecture are analyzed against various network theoretic metrics, including characteristic path length, network efficiency, assortativity, density, modularity, transitivity, etc. Hotellings T2 statistic is employed to determine the relative putative damage impacted by TBI upon various parts of the brain. To investigate the applicability of our framework to the investigation of human TBI, the temporal dynamics of cortical reorganization and atrophy due to trauma is analyzed longitudinally in 10 human TBI patients whose changes in cortical network configuration between 3 days and 6 months after injury are compared. Results. Calculation, statistical analysis and systematic mapping of network metrics using an average cortical atlas allow us to characterize TBI effects upon (1) specific locations in the brain, (2) global network architecture, and (3) network hubs with critical functional and structural role. In the case of simulated lesions, network assortativity is found to be a strong discriminant of cortical lesion effect as a function of TBI location in the brain. In the case of real life TBI data, appreciable changes in all network metrics are found as a function of time after injury. Conclusion. With the advent of the Human Connectome Project (humanconnectomeproject.org), exploration of cortical network properties has become an increasingly attractive way to probe the functional and structural organization of the brain, with a wide array of possible applications to clinical neurological and neurosurgical practice. Our effort is among a select group of studies whose purpose is to understand the role of pathology upon brain architecture. The results obtained here have potential applications to the treatment of clinical populations including victims of TBI due to vehicle accidents or falls, war veterans as well as collegiate or professional athletes.

A36 - Chaos in Astrophysics and Cosmology

Ed Iskander, *NMSU, Sandia National Lab, NASA-Ames*.

Just how prevalent is chaos in astrophysics and cosmology? It seems to be everywhere - from interstellar clouds to oscillating stars to our very own Solar System. There are many situations in which complex, non-linear equations have to be used to predict the internal structure of stars, the gravitational dynamics of galaxies, or the evolution of structure in the universe. In our Solar System, meteorites are known to follow chaotic trajectories which on occasion lead them to collide with Earth's atmosphere.

Recent advances in understanding complex astrophysical systems point towards the existence of low-dimensional chaotic behavior on various time and distance scales. Examples include seemingly random variations of oscillating stars which have been successfully interpreted in terms of non-linear interactions of regular acoustic modes. In this poster presentation I will give an an overview of chaos applications related to a variety of astrophysical objects and phenomena.

A37 - Growing Diverse Ensembles of Experts to Confront Non-Stationary Time Series

Abigail Jacobs[1], Cosma Shalizi[2], Kristina Klinkner[2], Aaron Clauset[1], [1]*University of Colorado at Boulder*, [2]*Carnegie Mellon University*.

Non-stationarities are common in time series arising from complex systems, where processes can undergo unforeseen shifts (or concept drift) and often have non-trivial or even non-Markovian structure. For such processes, searching for a single parsimonious model may be difficult or even impossible, and they are otherwise difficult to interpret. We introduce an algorithmic solution to this problem that grows an ensemble of experts (i.e., individual models), which automatically and efficiently adapts to unknown, possibly non-trivially non-stationary, sequences for online prediction. Our algorithm generalizes the classic approach of an exponentially weighted average forecaster, a meta-learner that adaptively combines the forecasts of different experts, in the context of online learning with expert advice. We prove bounds on the algorithms retrospective regret, i.e., the relative loss of the forecaster compared to the best expert at each interval. The growing ensemble of experts adapts more quickly to evolutionary changes in the system. The meta-algorithms system-agnosticism also allows the forecaster to work well to predict processes that are stationary, contain anomalies, or for which we cannot anticipate change points or characterize the type, rate, or scale of non-stationarity a priori. Furthermore, as we iteratively update the weight given to each expert to calculate the online weighted average, the behavior of the expert weights reveals information about the evolution of the system. Finally, through the lens of model selection, the expert weights can be used to both characterize the types (or presence) of non-stationarity as well as compare competing hypotheses or models in an online context. We apply this meta-algorithm to macroeconomic and paleoclimate data - systems in which we care about potential shifts described by (e.g.) recessions or climate change - and show that our growing experts algorithm performs well.

A38 - Experimental Bifurcation Diagram of an External Cavity Semiconductor Laser: Dynamical Regimes

Byungchil Kim, Alexandre Locquet, David Citrin, *Georgia Institute of Technology-CNRS*.

The dynamics of external-cavity semiconductor lasers (ECL) are known to be complex and difficult to control. The external cavity provides time-delayed optical feedback into the gain region of the laser; it is well known that this produces an infinite-dimensional dynamical system that can exhibit chaos. In view of the rich dynamical behavior as well as the technological importance of these devices, such as the use of chaotic dynamics for secure communication, radar, and random number generation, various aspects of the dynamics have been investigated. To our knowledge, however, a comprehensive study of the various dynamical regimes and their roles in the route to chaos, based on a detailed bifurcation diagram, has hitherto not been carried out.

While the behavior of a dynamical system can depend on many parameters, important insight can often be gained by fixing all but one parameter and then mapping out the dynamical regimes as that parameter is varied. The bifurcation diagram provides an easily apprehended depiction of how the dynamics undergo transitions between dynamical regimes as the control parameter is changed. Although bifurcation diagrams provide a standard way within the nonlinear-dynamics community to visualize the dependence of the dynamical regime on a control variable, there is an almost total lack of experimental bifurcation diagrams based on the measured optical intensity produced by an ECL. Nonetheless, there is a need for such measurements as they provide a way to test the reliability of theories of laser dynamics.

The dynamical regimes of an ECL biased relatively far above feedback and subjected to optical feedback from a distant mirror (long-cavity case) have been mapped out experimentally and are presented by means of bifurcation diagrams as a function of feedback strength. The bifurcation diagrams reveal detailed routes to chaos in these systems. In particular, our experimental results unveil a sequence of bifurcations involving limit-cycles, quasi-periodic and period-doubled behaviors, as well as intermittency between multiple coexisting attractors.

A39 - Flocking in Turbulent-like Flow

Nidhi Khurana, Nicholas T. Ouellette, *Yale University*.

Collective biological activity, such as swarms, flocks, or schools, has been the subject of many studies and has seen a significant modeling effort. Less work, however, has been done to understand the response of flocking models to nontrivial background flow fields, even though stability against flow is an important requirement for models since real animals live in fluid environments which are often turbulent. We numerically investigate the impact of turbulent-like flows on an animal aggregation model. We explore the behavior of a simple flock in a spatiotemporally correlated flow field generated by a kinematic simulation. We show that even when the flow velocities are significantly smaller than the individual animal speed, flocks tend to break into smaller units. We study the formation of these clusters and their relation to the underlying flow field.

A40 - Spatially Dependent Parameter Estimation and Nonlinear Data Assimilation by Synchronization on a System of PDEs

Sean Kramer, Erik Bollt, *Clarkson University*.

Applications to modeling ocean ecology by partially observed, because of cloud cover, satellite imagery data are discussed. Given multiple images of a dynamic scene describing chaotic reaction diffusion dynamics, spatially dependent parameters and model states are estimated to an assumed model form. Parameters and model states are observed by synchronization of the model to observed data, a process called autosynchronization. Furthermore, autosynchronization is effective when allowing for large regions of the dataset to be hidden from sensing. A two-component system of reaction-diffusion PDEs is used as a synthetic "observed" dataset.

A41 - Generating Real-Space Limit-Cycle Oscillation under Stationary DC Electronic Potential

Tomo Kurimura[1], Masahiro Takinoue[2], Masatoshi Ichikawa[1], and Kenichi Yoshikawa[1] [1]*Kyoto University,* [2]*Tokyo Institute of Technology*.

It is well known that biological motors such as flagella and cilia in living cells, are driven by the chemical potential gradient through the membrane, i.e., the driving force is DC electrical potential. It is noted that these biological motors work without any switching device, contrary to the currently available man-made DC electronic motors. Thus, it is of scientific value to try to construct DC electronic motor in the absence of switching device. Toward such goal, we may adapt the strategy to generate limit-cycle oscillation in real space under the application of stationary DC voltage. Recently, we have reported that rhythmic go-and-back motion of an aqueous droplet is generated under DC voltage on the order of 50-100V. It has also been shown that cyclic continuous motion is caused under DC voltage by adapting suitable spatial arrangement of the pair of electrodes under the similar voltage [1, 2]. As an extension of these studies, here we report the successful generation of oscillatory movement of a micro water droplet in an oil phase driven by DC electrical potential with the order of several volts. We show that the oscillatory motion is characterized as the limit cycle oscillation caused through Hopf-bifurcation. We have confirmed that the threshold voltage to induce the rhythmic motion is almost linearly proportional to the distance between the electrodes. We will interpret the mechanism of such unique motion under DC field in terms of phenomenological nonlinear differential equations.

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A42 - Statistical Properties of Avalanches in Networks

Daniel Larremore[1], Marshall Y. Carpenter, Edward Ott[2], Juan G. Restrepo[3], [1]*Harvard School of Public Health,* [2]*University of Maryland,* [3]*University of Colorado.*

We characterize the distributions of size and duration of avalanches propagating in complex networks. By an avalanche we mean the sequence of events initiated by the externally stimulated excitation of a network node, which may, with some probability, then stimulate subsequent excitations of the nodes to which it is connected, resulting in a cascade of excitations. This type of process is relevant to a wide variety of situations, including neuroscience, cascading failures on electrical power grids, and epidemiology. We find that the statistics of avalanches can be characterized in terms of the largest eigenvalue and corresponding eigenvector of an appropriate adjacency matrix that encodes the structure of the network. By using mean-field analyses, previous studies of avalanches in networks have not considered the effect of network structure on the distribution of size and duration of avalanches. Our results apply to individual networks (rather than network ensembles) and provide expressions for the distributions of size and duration of avalanches starting at particular nodes in the network. These findings might find application in the analysis of branching processes in networks, such as cascading power grid failures and critical brain dynamics. In particular, our results show that some experimental signatures of critical brain dynamics (i.e., power-law distributions of size and duration of neuronal avalanches) are robust to complex underlying network topologies.

A43 - Amplitude Control in Chaotic Systems

Chunbiao Li[1,2,3], J. C. Sprott[3], [1]*Southeast University, Nanjing, China,* [2]*University of Wisconsin,* [3]*Jiangsu Institute of Economics and Trade Technology, Nanjing, China..*

Amplitude controlling contributes to the chaotic signal application in practical engineering. By introducing control function in nonlinear terms, signals generated in chaotic system are amplitude-modulated partially or totally. Theory basement is given out and numerical simulation shows the effectiveness of control functions. The amplitude envelope is controlled to change with the control function while the Lyapunov exponent spectrum keeps constant.

A44 - Stochastic Competitive Population Dynamics: A Study on Evolutionarily Stable Dispersal Rate in Heterogeneous Spaces

Yen Ting Lin, Hyejin Kim, and Charles R. Doering, *Department of Physics, University of Michigan.*

We propose two individual-based patch models to study competitive population dynamics of two species with identical birth and death rates, but distinct dispersal rates and compete for limited resourses in heterogeneous environments. The objective is to explore whether the evolutionarily stable dispersal rate exists, and if so, how it depends functionally on various parameters of the systems. Combining conventional asymptotic analysis with a novel asymptotic analysis proposed by Lin et al, we obtained closed forms of asymptotic solutions of both systems, as well as the insight of the detail dynamical mechanisms.

The essential parameter of the system is identified to be the carrying capacity of each patch times the environmental variance. The conclusions are: (1) Given fixed dispersal rates of both species, the slower dispersers will always have evolutionarily advantage over a long period of time if the parameter is greater than a critical value that depends upon the ratio of the birth/death rates and the dispersal rates. In other words, slower dispersers have evolutionary advantages in more heterogeneous environments, as well as in a system with larger characteristic population size, and vice versa. (2) The evolutionarily stable dispersal rate exists only when the parameter is greater than a uniquely defined critical value which depends solely on the ratio of the birth/death rates. (3) We obtained asymptotically closed form of the evolutionarily stable dispersal rate as the response of various parameters of the systems. Most importantly, we understand how the evolutionarily stable dispersal rates depend on environmental variance.

Demographic fluctuations, which are often neglected in deterministic models, are identified to be the fundamental mechanisms for such regime shifts. Our analytical results are supported by large-scale exact numerical simulations. The limit behaviors reported by previous studies published by J. Dockery et al, D. Kessler & L.M. Sander, as well as J.N. Waddell et al confirm our general analysis, which provides a comprehensive understanding of such type of individual-based competitive population dynamics.

A45 - Core Percolation on Complex Networks

Yang-Yu Liu, Endre Csóka, Haijun Zhou, and Márton Pósfai , *Northeastern University.*

As a fundamental structural transition in complex networks, core percolation is related to a wide range of important problems, including combinatorial optimizations and network controllability. Yet, previous theoretical studies of core percolation have been focusing on the classical Erdös-Rényi random networks with Poisson degree distribution, which are quite unlike many real-world networks with scale-free or fat-tailed degree distributions. Here we analytically solve the core percolation problem for complex networks with arbitrary degree distributions. We find that purely scale-free networks have no core for any degree exponents. We show that for undirected networks if core percolation occurs then it is continuous while for directed networks it is discontinuous (and hybrid) if the in- and out-degree distributions differ. We also find that core percolation on undirected and directed networks have completely different critical exponents associated with their critical singularities.

Ref: Y.-Y. Liu, E. Csóka, H. Zhou, and M. Pósfai, Core percolation on complex networks, arXiv:1206.2550v2, Phys. Rev. Lett. (in press).

A46 - Dynamic Jamming of the Granular Polymers

Lena Lopatina, Cynthia Olson Reichhardt, Charles Reichhardt, *Los Alamos National Laboratory*.

We present an extensive study of the jamming behavior of two-dimensional semi-flexible granular polymers - a system composed of granular beads connected to form chains subject to lower bounds on the size of loops formed by beads in a chain. In previous work, we showed that the nature of jamming in granular polymer systems has pronounced differences from the jamming behavior observed for bidisperse two-dimensional disk systems at the jamming density [1,2]. We found that the jamming density decreases with increasing length of the granular chain due to the formation of loop structures, in excellent agreement with experiments [3]. The jamming density can be further reduced in mixtures of granular chains and granular rings, also observed in experiment [3]. In our current work, we investigate the response of the granular polymers to external loading by shearing the packing. We show that at low densities, the system unjams independently of the boundary conditions or shear rate. At high densities, for a slip wall, the system develops plug flow with a velocity equal to the shear rate. At high density, and for a non-slip wall, the system develops a shear band and finite stress. We show that the stress asymptotes to a value that increases with increasing density and decreases with increasing shear rate. The latter is attributed to shear band changes from wide and migrating at low load to very narrow and localized at high load. We also consider rigidity percolation measures and study both the average contact number of the grains in the packing as well as the distribution of contact number in the sample. We identify the dynamically changing rigid backbone in our sheared system and compare it to the fixed rigidity backbones found in percolating lattices.

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A47 - Symbolic Encoding in a Matched Filter Chaos-Based Communication

Alexandre Locquet[1], D.S. Citrin[1,2], M. Bennahmias[3], J. Laine[3], [1]*Georgia Tech-CNRS, Metz, France,* [2]*School of ECE, Georgia Institute of Technology,* [3]*Scieval LLC, Tarpon Springs, FL*.

Chaos-based communications use chaotic signals produced by nonlinear dynamical systems to convey an information-bearing message. The message decoding performance of a chaos-based communication in the presence of noise is usually lower than that of standard telecommunications that do not resort to chaotic systems. This limitation has been overcome recently by the discovery of a hybrid continuous-discrete system that allows for the existence of a matched (optimal) receiver. This matched receiver bears the promise of a decoding performance that is identical to that of standard communications.

We have developed a technique for encoding an information-bearing message within a chaotic signal produced by this novel hybrid system. The encoding is based on the control of the symbolic dynamics through small perturbations applied at discrete times. Specifically, we have identified a sequence of symbols to be the succession of positive and negative extrema of a dynamical variable of the hybrid system. Small perturbations are applied when the chaotic trajectory in phase space intersects with an extremal Poincaré surface of section. We have worked on the development of a high-speed FPGA-based version of this hybrid system and have been able to control a sequence of 5 symbols through a single perturbation and to achieve multi MBit/s bit rates.

A48 - Cutting and Shuffling: Mixing a Line Segment

Richard Lueptow[1], Marissa K. Krotter[1], Ivan C. Christov[2], and Julio Ottino[1], [1]*Northwestern University,* [2] *Princeton University*.

A deck of cards can be cut and shuffled to mix it, but rarely has cutting and shuffling been applied to mixing practical systems. In three-dimensional granular systems (such as mixing in a spherical granular tumbler), cutting and shuffling describes the underlying skeleton of the mixing that occurs allowing the exploration of complexity in the absence of the "typical" chaotic dynamics associated with hyperbolic periodic points, unstable manifolds, and stretching and folding. However, the computational study of a much simpler system, cutting and shuffling sub-segments of a line segment, is instructive. Illustrative examples of the mixing behaviors include situations for which the selected parameters lead to "good" mixing as well as pathological cases that violate the assumptions of the known governing theorems and lead to poor mixing. Using practical measures of mixing (the percent unmixed and the number of intermaterial interfaces), we find that good mixing can be achieved after a finite number of iterations of a one-dimensional cutting and shuffling map, even though such a map cannot be considered chaotic in the usual sense. Effective mixing can occur with only six or seven intervals of roughly the same length, as long as the rearrangement order is an irreducible permutation and the length ratio is properly chosen. This has implications for a number of mixing processes in which discontinuities arise either by construction or due to the underlying physics.

A49 - Relatively Coherent Sets as a Hierarchical Partition Method in time-dependent Chaotic Dynamical systems

Tian Ma, Erik M. Bollt, *Clarkson University*.

Finite-time coherent pairs in time-dependent dynamical systems have been studied recently. We present an extension to generalize the concept to hierarchically define relatively coherent sets based on adjusting the finite-time coherent sets to use relative measures restricted to sets those are developed iteratively and hierarchically in a tree structure of partitions and the resulting restricted Frobenius-Perron operators. Several examples are used to illustrate our method.

A50 - An FTLE Analysis of Active Fluids

John Mahoney, Kevin Mitchell, *University of California, Merced*.

Invariant manifolds are important barriers to passive tracers in 2D time-independent and time-periodic flows. Although these manifolds are no longer defined for time-aperiodic flows, the past decade of research has demonstrated the significance of the finite-time-lyapunov-exponent (FTLE) and lagrangian coherent structures (LCS) in this regime. Recently, barriers to front-propagation in (time-independent and time-periodic) fluid flows have been identified - so called burning invariant manifolds (BIMs). In order to understand the transport structure of fronts in generic flows, we define an analog of the FTLE for front-propagation in flows. This field and its ridges lie on a nontrivial submanifold of the entire phase space. This type of analysis finds natural application in the study of oceanic plankton blooms, turbulent combustion, and industrial chemistry.

A51 - Set of Wires to Simulate Tokamaks with Poloidal Divertor

T. Kroetz[1], Caroline G. L. Martins[2], M. Roberto[2], and I. L. Caldas[3], [1]*Universidade Tecnológica Federal do Paraná,* [2]*Instituto Tecnológico da Aeronáutica,* [3]*Universidade de São Paulo*.

Simple wires model have been proposed to simulate magnetic configurations in tokamaks. Here, we consider electric currents in five parallel infinite wires to obtain double-null magnetic surfaces with specific choices of magnetic axis positions, triangularity and elongation. As an example, we choose the position and the electric current of each wire to obtain magnetic surfaces similar to those expected in the tokamak ITER. Moreover, we also integrate the perturbed field line differential equation to simulate chaotic layers near the hyperbolic points and deposition patterns, at the divertor plate, observed in tokamaks. To simulate that, we add to the model a perturbing error field, due to asymmetries in the tokamak coils, and introduce a random colisional term to the field line mapping to reproduce escape pattern alterations due to particle collisions.

A52 - Randomness of Perturbed Dice Throw Dynamics

Nobuo Matsunaga, Yuzuru Sato, *RIES/Dept. of Mathematics, Hokkaido University*.

Dice throw as mechanical random number generator is known to be a pseudo-random dynamics [1], which is a dissipative system with final state sensitivity [2,3]. Randomness of the spots on a dice can be considered with the following two properties; (1) fairness: the basin measures of each final state are equal, and (2) predictability: each final state has large intermingled basins. Only under unrealistic condition of lack of energy dissipations, dice throw becomes unpredictable and fair by dynamics [4]. In this presentation, we study the "degree of randomness" of dice throw dynamics in inhomogeneous environments by using Nagler-Richter model [5]. Dice throw dynamics with perturbation in coefficient of restitution upon reflection is numerically investigated, and reproducibility of throws is discussed.

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A53 - Spatial Periodic Forcing Can Displace Patterns It Is Intended to Control

Yair Mau, Aric Hagberg, and Ehud Meron, *Ben-Gurion University of the Negev, Israel*.

Spatial periodic forcing of pattern-forming systems is an important, but lightly studied, method of controlling patterns. It can be used to control the amplitude and wave number of one-dimensional periodic patterns, to stabilize unstable patterns, and to induce them below instability onset. We show that, although in one spatial dimension the forcing acts to reinforce the patterns, in two dimensions it acts to destabilize or displace them by inducing two-dimensional rectangular and oblique patterns.

Poster Session B

Saturday Jan. 5, 7:30pm-9:30pm

B1 - Adaptive Stepping for Symplectic Integrators

C. Leland Ellison[1], A. S. Richardson[2], J. M. Finn[3], [1]*Princeton Plasma Physics Laboratory,* [2]*Naval Research Laboratory,* [3]*Los Alamos National Laboratory*.

Symplectic integrators exhibit good long-term numerical fidelity such as bounded energy error and trajectories lying on closed KAM surfaces (if the continuous system possesses such properties). From the Hamiltonian perspective, canonical coordinates allow implementation of known symplectic updates such as Crank-Nicolson and symplectic Runge-Kutta algorithms. From the Lagrangian perspective, variational integrators have emerged to derive symplectic algorithms in arbitrary coordinates from a discrete variational principle (action principle). Adaptive stepping is desirable to facilitate rapid computation. However, naive implementation of adaptive stepping can lead to problems, such as parametric instabilities or non-symplectic algorithms. Proper implementation of adaptive stepping will be discussed from the Hamiltonian perspective using generating functions and non-canonical brackets. In both the Lagrangian and Hamiltonian perspective, the phase space may be extended to include the simulation time as a new coordinate, which allows symplectic adaptive stepping without parametric instability. Examples will include guiding center motion and harmonic oscillators.

B2 - Modeling Computer Dynamics: Can Noise Beat Determinism?

Joshua Garland, Liz Bradley, *University of Colorado at Boulder*.

To fully understand modern computers, it is vital to first build effective and informative models of their dynamics. What this model should be, however, is up for debate. Traditional approaches employ linear, time-invariant (and often stochastic) methods such as autoregressive-moving-average and multiple regression. These strategies do not take into account any of the many nonlinear interactions that play important roles in computer performance.

An alternative approach is to model a computer as a deterministic nonlinear dynamical system — or as a collection of nonlinear dynamical systems (i.e., an iterated function system). In this view, the register and memory contents are treated as the state variables of the system. The logic hardwired into the computer, combined with the software executing on that hardware, defines the system's dynamics—that is, how the state variables change after each processor cycle. Delay-coordinate embedding can be used to reconstruct those dynamics (up to diffeomorphism) from a single observable, such as the processor load. Nonlinear models can then be constructed from these embedded dynamics using a variety of techniques.

To gain insight into which of these approaches is more appropriate in this important application, and why, we modelled the performance of several different programs running on an Intel i7 machine: one linear (multiple regression) and one nonlinear (the Lorenz method of analogues). We found that the success of the model depended on the program, which raises a larger research question: given a time series from an arbitrary dynamical system, how can one decide which modeling strategy will work better? We will propose some information-theoretic metrics for this task.

B3 - Is Transient Growth a Common Feature of Nonlinear Systems?

Jonathan McCoy, Colby College.

The ability to identify steady states and analyze their stability properties can be a key to understanding and predicting long-term system behavior. And yet, as a growing number of researchers are emphasizing, the role of short-term dynamics can be as significant as that of a system's attractors. Small perturbations can lead to transient growth, for example, even in the immediate vicinity of an attracting steady state. This seemingly counterintuitive phenomenon may not be all that unusual. It has been found in an overwhelming majority of ecological models, for example, though its origins are not fully understood. In this presentation, building on these ecological discoveries, I show that transient growth can expected in a wide range of nonlinear systems. In particular, using classic reaction-diffusion systems and biochemical oscillators as instructive test cases, I argue that generic feedback mechanisms associated with various instabilities promote transient growth as well.

B4 - Entanglement as a Classical, Nonlinear Phenomenon

Wm. C. McHarris, *Michigan State University*.

During the last several decades entanglement has emerged as one of the hottest concepts and catch-phrases in modern physics. It denotes the seemingly mysterious linkage between objects once connected but now separated so far that normal communication is impossible. For example, two electrons emitted in a singlet state retain this correlation even at infinite separations, such that a measurement on particle A yielding, say, spin-up instantaneously forces the wave-function of Particle B to collapse into its spin-down state. This communication occurs faster than the speed of light and is the epitome of Einsteins spooky action-at-a-distance and it is one of the reasons why orthodox quantum mechanics is fundamentally incompatible with relativity. However, during the last few years more and more scientists have been questioning the orthodox Copenhagen interpretation of quantum mechanics: Could it be possible that quantum mechanics contains fundamental nonlinear, even chaotic elements?! Many of the so-called paradoxes inherent in the Copenhagen interpretation have parallel explanations that can be explained far more logically in terms of nonlinear dynamics [WCM, Complexity 12(4), 12 (2007); J. Phys.: Conf. Series 306, 012050 (2011); and references therein]. For example, the seemingly random decay of radioactive nuclei can be reproduced by the butterfly effect, statistically producing an exponential decay curve. The most popular technique for exploiting entanglement is demonstrating that quantum systems can violate Bells inequality, which is impossible for classical systems and the inferences have been vast and far-reaching, at times becoming more philosophical than physical. Here I demonstrate that many of the so-called classical (and most experimentally useful) derivations of Bell-type inequalities tacitly assume uncorrelated particles. This means that one is comparing correlated with uncorrelated statistics rather than quantum with classical mechanics; in addition, often there has been subtle misuse of statistics, such as applying statistical conclusions to individual states. In fact, nonlinear systems can easily exhibit unexpected correlations, as evinced by the use of Tsallis nonextensive entropy [M. Gell-Mann and C.J. Tsallis, Nonextensive Entropy: Interdisciplinary Applications, New York: Oxford (2004)]. Such correlations can easily produce violations of Bell-type inequalities. I conclude by showing how nonergodic behavior can produce correlations that superficially appear to be non-local spooky action-at-a-distance. Nonlinear, even chaotic elements in quantum mechanics can provide the determinism so dear to Einstein; yet, they also require the statistical interpretation of the Copenhagen school of thought. Perhaps Einstein and Bohr were both right during their debates!

B5 - Anisotropic Transport beyond the Mass Tensor Approximation

Nicholas Mecholsky[1], Marco Fornari[2], Lorenzo Resca[1], Ian Pegg[1], [1]*The Catholic University of America/VSL,* [2]*Central Michigan University.*

The optimization of the electronic properties of thermoelectric materials are often rationalized using simple considerations based on the effective-mass approximation and the Boltzmann transport theory. This approach is relatively powerful and physically transparent but ignores important details of the underlying band structure such as multiple band-warped extrema and anisotropy. We have developed a different approach to locally approximate the energy dispersion that captures a wide class of band warping.

Using this form for the energy dispersion, the transport coefficients are calculated for fully anisotropic multi-band-warped crystal models. Our calculations are tested on technologically important materials and compared to a variety of other calculation methods for transport. Our results show that band warping is important in transport and must be included in transport calculations, and cannot be treated with a traditional mass-tensor approximation.

B6 - Dynamical Properties of the Triangular Bouncer

Bruce Miller[1], Matthew Holtfrerich[2], [1]*Texas Christian University,* [2]*Northern Arizona University.*

We investigate the dynamical properties of a Fermi bouncer with a triangular driving function using numerical simulations. A Fermi bouncer consists of a mass confined to move in one dimension that bounces on an oscillating floor. It will be shown that for the elastic case of this bouncer, both Fermi acceleration and stability islands exist. Also periodic and quasiperiodic motion can be found with the exception of period 1 motion. Furthermore it will be shown that the elastic version of the bouncer is a one parameter system and, when that parameter's value is changed, the behavior of the system can change drastically. However, if the collisions are inelastic, the system becomes a two parameter system which can change its behavior as either parameter is varied. The new parameter arises from a constant in the function defining the velocity dependence of the coefficient of restitution. In common with elastic collisions, the inelastic case shows periodic and quasiperiodic motion as well as stability islands but, not surprisingly, no Fermi acceleration. An interesting observation is that, when the coefficient of restitution function constant is varied, islands can be created or destroyed and, for some values, a complex pattern arises in the island structure.

B7 - Impact of Selection Strength on Evolution of Regulatory Networks

Garrett Mitchener, *College of Charleston.*

The Utrecht Machine (UM) is a discrete abstraction of a biochemical gene regulatory network (GRN). Virtual organisms based on the UM can perform any computation, given sufficient resources. Such simulations combine ideas from molecular genetics, artificial life, and evolutionary dynamics to form a platform for studying how GRNs evolve to solve problems. In this case study, selective breeding discovers agents that solve a data encoding problem: two bits of input are given to a sender UM, which must transmit them over time through a narrow synapse to a receiver UM, which must then reconstruct the original input. The receiver must also perform the secondary task of signaling when the computation is complete. Agents are scored based on how many bits they correctly transmit and how soon the receiver stops. Typical solutions stop after 20 or fewer time steps, and encode the two input bits as follows: activate the synapse very late or not at all to send 00, activate it very early to send 11, and activate it at intermediate times to send 10 and 01. The last major innovation is usually the ability to transmit both 10 and 01. A set of $10,000$ runs of this simulation for each of four breeding protocols reveals that details of the selection process have significant impact on population dynamics: Strong selection, in which fewer of the currently highest scoring organisms breed, leads to longer overall times to first perfect solution, generally longer genomes, more repairs to the timing mechanism after an improvement to the bit transmission mechanism has been found, and more atypical synaptic codes. Weaker selection, in which more medium scoring organisms can breed, has the opposite effects, and is more likely to discover improved partial solutions by breeding outliers, that is, organisms that do not achieve the highest score present in the population at the time. In addition, the time for the final innovation, that is, to find a perfect solution when some agent correctly transmits all but one bit correctly, is not exponentially distributed, but biased toward shorter times.

B8 - Detection of the Mediating Solution of Attractor Merging Crises

Tsuyoshi Mizuguchi, Makoto Yomosa, Naoya Fujiwara, Miki U. Kobayashi *Osaka Prefecture University*.

We focus on dynamical systems showing an attractor merging crisis (AMC). At the bifurcation point, a pair of strange attractors touches with a specific unstable symmetric solution, i.e., a mediating solution. We propose a method to detect these mediating solutions using time series analysis, which does not require an iterative procedure such as PIM triple method. In our method, a distance between a reference state and an image of corresponding transformation of the state is measured. The minimum of this quantity for a given orbit characterizes a degree of temporary symmetry of the orbit. By analyzing the minimum distance in the asymmetric side near the bifurcation point of AMC, an approach to the unstable symmetric solution is quantified. We apply this method to several symmetric chaotic systems showing AMC. An unstable symmetric torus is detected in the case of a repulsively coupled Stuart Landau system.

References:

[1] M. U. Kobayashi, T. Mizuguchi, Phys. Rev. E73 (2006) 016212.
[2] Y. Morita, N. Fujiwara, M. U. Kobayashi, T. Mizuguchi, Chaos 20 (2010) 013126.
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B9 - Continuum Simulations of Oscillated Granular Layers: Shocks and Patterns

Stefanie Moertl[1], Jonathan Bougie[1], Michael Hollowed[2], [1]*Loyola University Chicago,* [2]*University of Minnesota*.

We investigate vertically shaken granular systems using numerical solutions of continuum equations to Navier-Stokes order. When layers of particles are oscillated at accelerational amplitudes greater than that of gravity, shocks are created upon contact with the plate; additionally, standing-wave patterns form when the accelerational amplitude exceeds a critical value. We study the influence of shocks on pattern formation and propose a mechanism by which a non-uniform shock front drives standing-wave configurations. For a given layer depth and accelerational amplitude, varying driving frequency alters the shock strength as well as pattern wavelength; increasing layer depth produces stronger shocks and longer wavelengths for a given frequency. In this study, we express the proposed mechanism in terms of dimensionless variables and demonstrate empirically that these relationships can be successfully non-dimensionalized by layer depth and driving frequency. This research is supported by the Research Corporation for Science Advancement and the Loyola Undergraduate Research Opportunities Program.

B10 - Lattices of Entangled Cupolets

Matthew Morena, Kevin M. Short *University of New Hampshire*.

This talk will discuss applications of a particular control technique that can be used to very efficiently stabilize a chaotic system onto a large subset of the unstable periodic orbits that are typically embedded in the system. The control method is adapted from one developed by Hayes, Grebogi, and Ott, and the resulting (stabilized) orbits are known as cupolets (Chaotic, Unstable, Periodic, Orbit-LETS). Cupolets exhibit the interesting property that a given set of controls will uniquely identify a cupolet, independent of its initial condition. Previous research demonstrated how to entangle cupolets from two interacting chaotic systems by inducing a pair of cupolets into a state of mutual and self-sustaining stabilization, in a manner that may be an analog of quantum entanglement. The two-way interaction between entangled cupolet pairs is managed by an exchange function, which reformulates each cupolets symbolic dynamics into the control information needed to maintain the stability of the partner cupolet of the entangled pair. In some instances, cupolet entanglement may be generated without the need for an exchange function, and certain properties of chaotic behavior actually increase the likelihood of physical systems entering into chaotically-entangled states. In this talk, we will describe a further application of chaotic entanglement. When spatial-dependence is imposed on the interaction between chaotic systems, cupolet entanglement may be induced when the states of two cupolets are close enough to interact. Pairs of cupolets may then be assembled into various geometric structures that range from a simple tripartite lattice to more involved patterns. Examples of such lattices will be presented and the talk will conclude with some discussion of future research directions.

B11 - Quantifying Stretching and Rearrangement in Epithelial Sheet Migration

Rachel Lee, Kerstin Nordstrom, Douglas Kelley, Nicholas Ouellette, Wolfgang Losert, *University of Maryland*.

Although understanding the collective migration of cells, such as that seen in epithelial sheets, is essential for understanding diseases such as metastatic cancer, this motion is not yet as well characterized as individual cell migration. Here we adapt quantitative metrics used to characterize the flow and deformation of soft matter to contrast different types of motion within a migrating sheet of cells. Using a Finite-Time Lyapunov Exponent (FTLE) analysis, we find that - in spite of large fluctuations - the flow field of an epithelial cell sheet is not chaotic. Stretching of a sheet of cells (i.e., positive FTLE) is localized at the leading edge of migration. By decomposing the motion of the cells into affine and non-affine components using the metric D2min, we quantify local plastic rearrangements and describe the motion of a group of cells in a novel way. We find an increase in plastic rearrangements with increasing cell densities, whereas inanimate systems tend to exhibit less non-affine rearrangements with increasing density.

B12 - Unification of Ion Channel and Electrical Restitution-Based Viewpoints in the Study of Cardiac Action Potential Dynamics

Niels Otani, *Cornell University*.

The study of action potential dynamics in the heart is critical for developing a mechanistic understanding of many of the most dangerous rhythm disorders observed in modern cardiology. Research on this topic has followed two, largely independent tracks–those employing detailed ion channel models, and those employing electrical restitution function-based models that follow quantities such as the action potential duration (APD), the diastolic interval (DI), and memory. Ion channel models have the advantage of representing the actual processes taking place within membranes of cardiac cells, but can be very complicated to diagnose and understand. Electrical restitution models are much more accessible conceptually, but are generally phenomenologically conceived and thus have no direct ties to the ion channel dynamics. In our study, we show a simple method by which a linearized version of the APD restitution function and memory relationships can be derived directly from an ion channel model for the case of constant pacing in a single cell. As is true for any restitution function-based system, susceptibility of the system to alternans (i.e., period-2) behavior is easily determined from these new relationships. Furthermore, the relationships display explicitly how the memory in the system, expressed in the form of amplitudes of the memory eigenmodes, modifies the classical restitution relationship between the APDs and DIs. Finally, the new relationships show why it is that apparently different dynamics can be observed when different methods are used to measure the APD (e.g., APD85, APD90, etc.), thereby providing guidance on which measure should be used in experiments. We conclude that these new restitution relationships have the capability to provide insight into the action potential dynamics of ion channel models that is normally reserved for models defined in terms of electrical restitution.

B13 - Non-linear Dynamics of the Human Processual Phenotype

James Palmer, *Dept. Family Medicine, University of Colorado Denver School of Medicine*.

This presentation discusses the processual, emergent and nonlinear dynamic nature of the human phenotype and how it can be described and understood with applied math and concepts based in the complexity sciences and relevant maths. Several existing mathematical applications of nonlinear dynamics to analysis of clinical COPD (Chronic Obstructive Pulmonary Disease) phenotypes clinical phenotypes will be described.

Core Concept: The Clinical Processual Phenotype takes as its starting point the multi-dimensional and multitudinous points of dynamic human engagement with existence as self, others and environments, built and natural. A key unifying proposition is that variability is an intrinsic and essential aspect of the processual phenotype and of the integration and coherence of phenotype engagement with existence. The complexity sciences and associated maths provide core foundations of the processual phenotype concept.

The Processual Phenotype provides the Qualities and Capacities of variability of engagement required for viability of existence, with particular regard to the fundamental objectives of survival, reproduction and - importantly for humans - the determination of dispositional tendencies and motivational dynamics by the evaluation and assessment of value in both the biological and social sense. The Human Processual Phenotype enables an extended quantity and enhanced quality of engagement by means of sophisticated variability of engagement. The expanded dynamics and possibilities of engagement, such as nonlinear dynamics of heart rate variability and appropriate variation in emotion regulation, increase the chances for survival, reproduction and generation of value. The added trans-phenotype dimension of variability of engagement has an integrating and coherence function that crosses and unifies other dimensions of the clinical phenotype. The processual phenotype is an applied research theory construct which provides a unifying dynamic mind-body, holistic perspective of the embodied person.

Applied Math for Phenotype Analysis: The construct will be illustrated with examples of how non-linear dynamics and concepts from the complexity sciences are already being used to analyse and understand clinical COPD (chronic obstructive pulmonary disease) phenotypes. For example the use of detrended fluctuation analysis of Peak Expiratory Flow as a predictive respiratory disease activity biomarker of exacerbations (attacks, crises) of COPD. The use of Fractal analysis of imaging to understand airway geometry and to analyse the progression of emphysema will be described. The relationship of self-affine and self-similar variability analysis of structure, function and phenotype trajectory will be briefly related to the concept of symmetry and the connection of symmetry to laws of conservation (Noethers Theorem).

Generation of New Research: Several possible paths for additional research will be described.

B14 - Chimera States on Periodic Spaces

Mark Panaggio, Daniel Abrams, *Northwestern University*.

In nature, arrays of interacting incoherent oscillators often spontaneously synchronize. This occurs in the footfalls of pedestrians walking on a bridge, the flashing lights produced by swarms of fireflies, and even in the contractions of heart cells. Although incoherence and synchronization are the norm in these systems, occasionally complex spatiotemporal patterns can exist. Kuramoto and Battogtokh discovered one such pattern in which spatial regions of coherence and incoherence can coexist. Latter dubbed a chimera state, this type of pattern has surfaced in a variety of systems and was recently observed in experiments. I will use an analytical approach to explain how these states arise and discuss their various manifestations in periodic spaces including a one-dimensional ring and the two-dimensional surface of a flat torus. These developments shed light on how synchrony can break down in nature and suggest that complex patterns such as chimera states may be more common than initially thought.

B15 - Density Inversion in Oscillating Granular Layers

Joshua Panfil[1], Jon Bougie[1], Jennifer Kreft Pearce[2], Veronica Policht[3], [1]*Loyola University Chicago,* [2]*Roger Williams University,* [3]*University of Michigan-Ann Arbor*.

We investigate density inversion in shaken granular layers using three-dimensional, time-dependent continuum simulations. These simulations numerically solve continuum equations to Navier-Stokes order for a layer of uniform, inelastic, frictionless spheres on a vertically oscillating plate. Steady-state density inversion, in which a higher density region sits atop a lower density, gas-like region below, occurs for high accelerational amplitudes of the plate. For lower accelerational amplitudes, we observe time-dependent motion correlated to the movement of the plate. We investigate the transition from cyclic time-dependence to steady-state density inversion for varying dimensionless shaking strength S as a function of control parameter Γ, where Γ is the dimensionless accelerational amplitude of the plate. In each case, the density profile of the layer exhibits a cyclic oscillation at the driving frequency for low Γ. The response frequency matches the driving frequency as Γ increases through the transition. However, the amplitude of time-dependent response drops as Γ exceeds a critical value, representing a transition to a nearly steady-state density. Comparisons between continuum simulations and experimentally verified molecular dynamics simulations show consistent results between the two simulation methods. This research is supported by the Research Corporation for Science Advancement and by the Loyola Undergraduate Research Opportunities Program.

B16 - Mixing by Cutting & Shuffling in 3D Granular Flow: Exploring Relations to Piecewise Isometry

Paul P. Park, Paul B. Umbanhowar, Julio M. Ottino, Richard M. Lueptow, *Northwestern University*.

We study chaotic dynamics of granular flow in a spherical tumbler rotating alternately about two orthogonal axes (a blinking spherical tumbler). Under certain conditions, it is useful to assume an infinitely thin flowing layer (ITFL) in which mixing occurs through cutting and shuffling. The degree of mixing by cutting and shuffling is sensitive to the combination of rotation angles about each axis (protocol), but no clear method exists for understanding this class of mixing in three-dimensional (3D) granular flow. In the limit of an ITFL, 3D granular flow in a half-full sphere can be reduced to dynamics on a hemispherical shell (2D). For certain protocols, Poincare maps on this shell show patterns that include elliptic regions. A Poincare map tracing points seeded at the edges of the hemisphere after each rotation is reminiscent of partitions generated by piecewise isometries (PWI), such as PWI on an isosceles triangle. Previous work has considered the dynamics of a blinking spherical tumbler with an ITFL as a PWI, but its relationship to traditional definitions of PWI is unclear. Our goal is to more directly link mixing dynamics in the blinking spherical tumbler to the larger body of work done in PWI, and thereby establish methods to qualitatively and quantitatively analyze mixing by cutting and shuffling in higher dimensions.

B17 - Automatic Sorting of Point Pattern Sets Using Minkowski Functionals

Joshua Parker, Eilon Sherman, Matthias van der Raa, Larry Samelson, Wolfgang Losert, *University of Maryland*.

Point patterns arise in many different areas of physical and applied research, reflecting the internal dynamics of the pattern formation process. Often by experimental replication and variation or looking over different time scales, one can generate sets of patterns that may or may not be fundamentally different. We introduce here a automatable numerical taxonomy procedure for clustering point pattern sets using their approximated Minkowski functionals. We demonstrate that this procedure outperforms current methods, even when the patterns are drawn from very similar processes. We highlight the use of this routine for automatically analyzing sets of patterns, and in particular super-resolution images of fluorescently labeled proteins. Overall, we find that this routine is a robust method for sorting point pattern sets, and provides meaningful insight regarding the homogeneity of spatial processes.

B18 - Integrating Timescales of Ecological and Evolutionary Processes in an Intraguild Predation System

Swati Patel, Sebastian Schreiber, *University of California Davis*.

Until recently, ecological and evolutionary processes have been studied predominantly in isolation of one another because they were thought to occur on separate timescales, with evolution occurring much more slowly than ecological processes. With recent evidence of more rapid evolution, biologists are now trying to understand the interplay between these two processes and how they affect the overall dynamics of the populations involved. Here, we focused on understanding these dynamics in a particular system of interacting populations, called intraguild predation. Intraguild predation is a three-species network, in which a top predator consumes a prey as well as the common resource that they share. Using a system of partial differential equations, we model the population dynamics of the three species to depend, in part, on all of the interaction strengths between species. These interaction strengths in turn depend on the dynamically evolving phenotypes of the species, which enables us to study the evolutionary affects on the system as well. We focus on understanding the impact of the evolution of the predator on the overall dynamics. Using singular perturbation theory analyses, we find that small evolutionary changes can sometimes lead to sudden changes in the species composition. Furthermore, we studied how changes in the speed of evolution influence the population dynamics and find that faster evolution can, in some cases, cause cycles to emerge from stable equilibria, while in other cases, it can stabilize cycles into equilibria.

B19 - Tunneling and Electron Conductances in Chaotic and Regular Quantum Dot Systems

Louis Pecora[1], Ming-Jer Lee[2], Thomas Antonsen[2], Edward Ott[2], [1]*Naval Research Laboratory,* [2]*University of Maryland* .

Transmission of electrons through quantum dots can be controlled down to the level of allowing one electron at a time through the dot. The conductance of this current through quantum dots is regulated by the tunneling barriers from the leads to the dots and the type of wave functions in the dot itself. Although the dependence of the conductance on the wave function has been acknowledged since the early 1990s most of the theory of quantum dot conductance has assumed chaotic dot geometry and very narrow (point contact) tunneling barriers. We have developed a theory of tunneling through an open quantum dot system with two leads (in and out) and tunneling barriers at the lead-dot junctions. We also include electron-electron interactions via capacitive charging and allow the leads and barriers to be arbitrarily wide at the dot interface (not merely point contacts). With this theory we examined regular as well as chaotic dot geometries. We find that the distribution of conductances varies greatly (often by several orders of magnitude) with the dot geometry and, hence, the (classical) dynamics. It is often the chaotic dots that actually have a narrower distribution of conductances than the regular dots. Much of this can be explained by invoking a random plane wave approximation to the electron wave functions for the chaotic dots which explains the narrower conductance distributions. Interestingly, these results are similar in some ways to tunneling in closed, double-well quantum systems [1].

[1] Chaos Regularization of Tunneling Rates, L. Pecora, D-H. Wu, H. Lee, M-J. Lee, T. Antonsen, and E. Ott, Physical Review E, Rapid Communications, volume. 83, No. 6, 065201(R).

B20 - Identifying and Quantifying Interactions in a Laboratory Swarm

James Puckett, Douglas H. Kelley, Nicholas T. Ouellette, *Yale University*.

Emergent collective behavior, such as in flocks of birds or swarms of bees, is exhibited throughout the animal kingdom. Many models have been developed to describe swarming and flocking behavior using systems of self-propelled particles obeying simple rules or interacting via various potentials. However, due to experimental difficulties and constraints, little empirical data exists for characterizing the exact form of the biological interactions. We study laboratory swarms of flying *Chironomus riparius* midges, using stereoimaging and particle tracking techniques to record three-dimensional trajectories for all the individuals in the swarm. We describe methods to identify and quantify interactions by examining these trajectories, and report results on interaction magnitude, frequency, and mutuality.

B21 - Dynamics by the Dozen: Involving Many Levels of Students in Nonlinear Dynamics Research

Randall Tagg, Masoud Asadi-Zeydabadi, *University of Colorado Denver*.

Nonlinear dynamics has the feature that it is conceptually and mathematically challenging and yet ubiquitous in its applications. Indeed, one of the appeals of the subject is the universality of some of its frameworks and results. We are attempting to take advantage of such wide applicability in order to involve an unusual range of participants in nonlinear dynamics research. This range spans from postdoctoral to K-12 students as well as teachers. The poster will feature our collaboration to guide several projects in various depths, including Hamiltonian chaos in optical propagation, bifurcations in circadian rhythms in plants, nonlinear interaction of actuator systems, vascular dynamics, neural systems modeling, and fluid instabilities. A key arena in which novices can participate effectively is in the search for applications. A particular applied area where we are focusing is biomedicine.

B22 - Adaptive Pinning Synchronization Control Applied to a Network of Autonomous Vehicles

Luis Felipe R. Turci, Mateus M. R. Simões, *Federal University of Alfenas - UNIFAL-MG, Brazil*.

In this work we analyze and apply the fully adaptive pinning control strategy for the synchronization of processes hold in complex network agents when network topology changes along time; particularly, we consider a network of random walker mobile agents in which the topology is determined by the relative position of network agents.

B23 - Desynchronization in Evolving Complex Networks

Luis Felipe R. Turci, *Federal University of Alfenas - UNIFAL-MG, Brazil*.

The synchronizability problem in complex networks is a solved problem, and synchronization conditions for complex networks with fixed topology are well known. In this work we analyze the synchronization behavior of evolving complex networks in which new nodes are periodically added to the network.

B24 - Neural Network Function – Density or Geometry?

Anca Radulescu, Sergio Verduzco, *University of Colorado at Boulder*.

Recent studies have used graph theoretical approaches to investigate the organizational principles of brain networks, with nodes and edges defined according to modality appropriate scales. Certain generic topological properties of the human brain architecture have been studied (such as modularity, small-worldness, the existence of hubs and other connectivity density patterns), as properties that may be used to better understand neural processes. In our work, we explore two key conditions for optimal function in brain networks. First, the requirement for a well-balanced adjacency matrix: the corresponding bidirectional graph should appropriately combine robust features (e.g., fully connected populations) and random edges (e.g., due to synaptic probing) so as to allow some flexibility, yet also render sufficient stability for convergence during a cognitive process such as learning. Second, the requirement for a well-balanced set of connection strengths (i.e., the weights on adjacency edges), hence an efficient connectivity matrix driving optimal dynamics in the system. We discuss in particular, in a low dimensional model, how spectral properties of the adjacency matrix (e.g., dependence of edge density, robustness to edge geometry) reflect into spectral properties of the connectivity matrix, and, further along, into properties of the Jacobian matrix of the dynamical system that "uses" the weighted edges for dynamic coupling.

B25 - Jamming to Clogging Transitions for Systems with Obstacle Arrays

Charles Reichhardt, Zohar Nussinov, Cynthia Reichhardt, *Los Alamos National Laboratory*.

Jamming can occur in systems consisting of collections of particles when the response of the system changes from a fluidlike state that can easily flow to a state that acts like a solid. For a loose collection of grains, jamming can occur as a function of density, where the grains readily flow at low densities but with increasing density undergo a transition to a jammed state at point J. Liu and Nagel have proposed that there may be a universal jamming phase diagram as a function of density, load, or temperature that may also include the glass transition. Here we propose that the density of fixed obstacles or quenched disorder can be considered as a new axis for the jamming phase diagram, since the disorder causes the system to jam at densities below point J. For a small number of obstacles, the system exhibits jamming behavior; however, for higher disorder density, there is a crossover to a behavior that we term clogging rather than jamming since the stuck states are highly heterogeneous, fragile, and exhibit memory effects. Our results imply that clogging is a distinct phenomenon from jamming with very different behaviors. These results are of relevance for particle flow in porous media, depinning transitions, and jamming in crowded environments.

B26 - Non-neutral Magnetic Vortex Dynamics

Steve Richardson, S. B. Swanekamp, *Naval Research Laboratory, Pulsed Power Physics Branch, Plasma Physics Division*.

Non-neutral magnetic vortices have been observed in electromagnetic particle-in-cell (PIC) simulations of plasmas where density gradients exist. When plasma dynamics on the length scale of the electron inertial length (c/ω_{pe}) and the time scale of electron motion ($t \sim 1/\omega_{pe}$) is considered, charge separation and electron inertia effects become important. Relativistic effects may also be important in a regime where very large current densities exist ($|J| \gg v_{Te}/en_e$). This can arise when a large magnetic field pushes on an initially unmagnetized plasma (e.g., in a plasma opening switch, dense plasma focus, etc). One phenomenon which can occur in this regime is the formation of magnetic vortices, in which a strong azimuthal current sustains an axial magnetic field. An associated charge separation gives rise to a radial electric field, and the electron motion is primarily an $E \times B$ drift in the azimuthal direction. For short times ($t \ll 1/\omega_{pi}$), the ions are motionless and the vortex is a steady-state solution to the two-fluid approximation to the kinetic equations. Gradients in the background plasma density can cause the vortex to propagate along density contours, and can transport magnetic fields into an unmagnetized plasma. Theory indicates that field penetration must be accompanied by energy dissipation and the balance between electromagnetic energy, thermal, and directed kinetic energy can be verified. On longer time scales ($t \sim= 1/\omega_{pi}$), the strong electric fields in the vortex can accelerate the ions radially outward from the plasma disrupting the vortex and giving rise to a bi-modal ion velocity distribution function. In plasmas with multiple ion species, this can lead to a spatial separation of the ion species. In the fixed-ion limit, the two fluid equations for a magnetic vortex reduce to a fairly simple form which has a semi-analytic solution. This solution has been used as an initial condition in a PIC code, in order to study the dynamics of vortex propagation and the effect of gradients in the background plasma density.

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B27 - Dynamical Instabilities in Coupled Huygens Pendulums

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The dynamics of two coupled pendulums was studied in its analogy with the coupled clocks described originally by C. Huygens in XVII century. A simple model resulted from the classical mechanics equations for two pendulums of mass m coupled by their fixation to a moving wall of mass M. The small amplitude regime of oscillation has well known normal modes whose symmetry permits the extension of these modes into the nonlinear oscillation condition. Anti-phase oscillations of the pendulums are the most robust with respect to dissipations. In the high non-linear regime the system shows resonant energy transfer between modes whose frequencies cross as the total energy decreases due to dissipation. Numerical solution of the system, show a strong dependence of the dissipation rate of the total energy according to the symmetry of the oscillating mode. The system shows dynamical bifurcations from periodic into quasi-periodic and chaotic regimes as a result of the instabilities due to mode coupling. When very low dissipation is considered the system evolves through quasi-hamiltonean oscillations, which permits the determination of spectrograms clearly showing the nonlinear mode frequencies and their crossing instabilities. Experimental verification of the theoretical instabilities was obtained with a simple pair of coupled pendulums constructed in our laboratory.

B28 - Nonlinear Amplification of RF Effects in Biological Magnetic Sensing

Gregory Robinson, *University of Colorado at Boulder*.

Much attention has recently developed around chemical reactions that depend on applied magnetic fields as weak as earths. This interest is largely motivated by experiments that implicate the role of spin-selective radical pair recombination in biological magnetic sensing. Existing literature uses a straightforward calculation to approximate the expected lifetime of coherent radical pairs as a function of the minimum Zeeman-resonant RF amplitude that is observed to disrupt magnetic navigation. Applying the same approach to new behavioral data (by Phillips et al.) indicates a suspiciously long coherence lifetime, and has therefore shed doubt on whether the coherent radical pair hypothesis is valid for rodents. But we show that chemical nonlinearities can preclude direct computation of coherence lifetime without considering the cellular signalling mechanisms involved, and may explain how some animals compass sense can be disrupted by weak signals like commercial broadcast radio. In particular, we demonstrate how an autocatalytic cycle can introduce threshold effects on the disruption sensitivity to applied oscillatory magnetic fields. We will show examples in the mean-field limit and, if time permits, consider the consequences of noise and fluctuations in the Freidlin-Wentzell picture of perturbed dynamical systems.

B29 - (Relativistic) Lattice Boltzmann Equation with Non-Ideal Equation of State

Paul Romatschke, *University of Colorado at Boulder*.

The relativistic Boltzmann equation for a single particle species generally implies a fixed, unchangeable equation of state that corresponds to that of an ideal gas. Real-world systems typically have more complicated equation of state which cannot be described by the Boltzmann equation. The present work derives a 'Boltzmann-like' equation that gives rise to a conserved energy-momentum tensor with an arbitrary (but thermodynamically consistent) equation of state. Using this, a Lattice Boltzmann scheme for diagonal metric tensors and arbitrary equations of state is constructed. The scheme is verified for QCD in the Milne metric by comparing to viscous fluid dynamics.

B30 - Experimental Boolean Kuramoto-like Oscillators: The Hunt for Chimera States Using Reconfigurable Chips

Damien Rontani, David P. Rosin, and Daniel J. Gauthier, *Duke University*.

Kuramoto oscillators have received much attention as a paradigm to understand collective phenomena in large networks of coupled dynamical systems. Analysis of these networks has led to the discovery of new network states such as the chimeras, where the phases of the oscillators are simultaneously ordered and disordered depending on their position in the network. Two recent experiments with optical [1] and chemical [2] oscillators have observed chimeras and hence motivate additional experiments to search for similar behaviors using autonomous Boolean networks [3]. We will describe our recent discovery of a method to realize large networks of Kuramoto-like Boolean phase oscillators using autonomous logic gates on a field programmable-gate array (FPGA). We have realized a Boolean-analog of diffusive coupling with both attractive and repulsive interactions and with or without time delays along the network links. We report on the observation of global synchronization in a large network of phase oscillators and a transition to an incoherent state as the coupling strength is varied. Our study provides a new technique for realizing large-scale experiments with phase oscillators that will allow us to start the hunt for chimera states and other complex organizational behaviors in autonomous Boolean networks.

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B31 - Turbulence Particle Transport Driven by Plasma Drift Waves

Kauê Rosalem, M. Roberto, I.L. Caldas, *Instituto Tecnológico de Aeronáutica, Brazil*.

Many plasma theoretical models investigate the drift wave plasma turbulence phenomena and the associated particle losses due to the radial transport process. The particle confinement performance in tokamak plasmas requires a control of drift waves, and the reversed magnetic shear may contribute to drift wave turbulence reduction. This work applies a drift wave turbulence model to integrate numerically the guiding center equation of motion in terms of action and angle variables. The electrostatic potential amplitude and the magnetic shear are the control parameters of this dynamical system. The particle transport is caused by the chaotic particle trajectories in the Poincaré maps perturbed by resonant perturbations. We investigate the transport dependence on magnetic shear for coherent oscillations and a power spectrum characterized by a peak. The simulations incorporate a mean radial electric field and the lowest angular frequency in the drift wave spectrum.

B32 - Hamiltonian Wave Dynamics on the Genesis of Eddies from Slow Waves in Rotating Flows

Amrik Sen, Keith Julien, Annick Pouquet, *University of Colorado at Boulder*.

We present a detailed wave turbulence theory for rotationally constrained flows governed by an asymptotically reduced set of equations, known in the absence of stratification as the reduced rotating hydrodynamic (R-RHD) equations. We demonstrate, analytically, for the first time to our knowledge, the existence of a wave-eddy coupling within what is now generally referred to as the slow manifold of the flow. This paves a way to understand the genesis of geostrophic eddies from wave dynamics in rotating flows. The significance of this result is further enhanced by the fact that it counters the hitherto accepted notion of the existence of a singularity in wave turbulence formalism in the two dimensional manifold using three-wave interactions. The R-RHD equations, that are asymptotically valid within the slow manifold, filter fast inertial waves from slow inertial spatially anisotropic waves evolving on eddy turnover timescales, the latter breeding the small amplitude eddies. The temporal separation of waves and eddies and the associated wave-eddy decoupling is well established in quasi-geostrophic theory where the fast wave frequencies are bounded from below by strong stratification. No such restrictions exist for weakly stratified or unstratified rotating flows. The solutions for the energy spectrum presented in this paper coincide with the results of numerical simulations of unstratified flows reported recently by other researchers and at least one theoretical prediction based on an asymptotic quasi-normal Markovian (AQNM) closure model.

B33 - Generalized Complex Ginzburg-Landau Equation: Local-to-Nonlocal-to-Global Coupling

Gautam Sethia[1], Abhijit Sen[1], George L. Johnston[2], [1]*Institute for Plasma Research, Bhat, India,* [2]*Edu Tron Corp., Winchester, MA, USA*.

We generalize the one-dimensional complex Ginzburg-Landau equation by replacing its diffusive coupling by a nonlocal coupling term which enables us to span through local-to-nonlocal-to-global coupling in a continuous fashion. We take the system to be of finite size with periodic boundary conditions. We investigate the stability of its plane wave solutions and find that the stability condition significantly depends upon the degree of nonlocality and the wave number of the plane wave solution. In the local limit, the Benjamin-Feir criterion gets modified by the nonlocality parameter and the Eckhaus criterion is replaced by a number of conditions involving nonlocality parameter and are different for different wave numbers.

B34 - Nonlinear Oscillations of Microdisk Resonators

Alexander Slawik, Daniel M. Abrams, *Northwestern University*.

Microdisk resonators are micron-scale optical devices that can be treated as strongly nonlinear oscillators. A four dimensional system of differential equations governs the complex amplitude of the EM-field, the number of free electrons, and the temperature in the disk. This model has rich dynamics, including regions of bistability, hysteresis, and local and global bifurcations. In physically relevant regions of parameter space the variables evolve on well-separated time scales, allowing for asymptotic analysis of the behavior and quantitative prediction of useful optical properties.

B35 - Homeostasis and Genetic Robustness are Correlated in Responsive Biochemical Networks

Zeina Shreif, Vipul Periwal, *National Institutes of Health*.

The evolutionary fitness of an organism, a unitary concept, is defined as the likelihood that the lineage of that organism survives. A priori, this fitness requires that the organism can adapt to external/non-genetic perturbations (homeostasis) and that the transmitted genotype is robust to internal/genetic changes (genetic robustness) so as to preserve the success of the progenitor phenotype. Biologically and mathematically, a priori, these two concepts are unrelated: Homeostasis is a dynamic property and is a direct product of natural selection. Genetic robustness is a static property that is unnecessary for homeostasis. It is, however, essential for evolution to occur and seems to coexist with homeostasis in many biological processes. Despite its central role in the evolutionary process, the rationale for selection for genetic robustness is still controversial. Based on observed examples of biological systems, a correlation between the evolution of homeostasis and that of robustness has been proposed. However, the origins of this putative relationship have never been investigated in a general theoretical context.

Here, we find a strong statistical correlation between adaptive homeostasis and genetic robustness in N-node information-propagating biochemical networks. Such networks detect cues from their environment and react appropriately, making them fundamental components determining the homeostasis of an individual. Our results provide a foundation for the unitary character of evolutionary fitness. We investigate the scaling properties of these networks and extract topological motifs that are necessary and/or sufficient to achieve adaptive homeostasis and/or genetic robustness. Furthermore, we map out the robustness/homeostasis space of these topologies. This correlation and the identification of design principles renders the deciphering and reconstruction of complex biological networks more feasible as we narrow down the search space for possible design principles in biology.

B36 - Hierarchical Paths to Synchronization in Networks with Community Structure

Per Sebastian Skardal, Juan G. Restrepo, *University of Colorado at Boulder* .

The study of emergent collective behavior in large networks of interacting dynamical systems represents a large area of complexity theory. In the research of these systems, a main question lies in understanding how different network topologies affect the dynamics of interacting agents and give rise to macroscopic phenomena. Here we address this question by studying synchronization of Kuramoto oscillators in networks with modular, or community, structure. In particular, we study the hierarchical path of synchronization in such networks, which often first occurs locally within each community, then globally as communities synchronize with one another. We first consider a community-wise mean-field network structure where we can obtain analytical results that completely describe hierarchical synchronization by applying the dimensionality reduction technique of Ott and Antonsen first on a local scale within each community, and then on a global scale where communities synchronize with each other. Next, we use these analytical results to predict both local and global synchrony in modular networks where the detailed topology is preserved and find excellent agreement. These results help shed light on the hierarchical paths of dynamical processes in modular networks.

B37 - Effects of Degree-Frequency Correlations on Network Synchronization

Per Sebastian Skardal[1], Jie Sun[2], Dane Taylor[1], and Juan G. Restrepo[1], [1]*University of Colorado at Boulder*, [2]*Clarkson University*.

During the last several decades models for network-coupled dynamical systems, such as the Kuramoto model, have proven very useful for uncovering generic mechanisms behind complex dynamical processes such as network synchronization. Recent studies have found that certain classes of correlations can give rise to enhanced synchronizability and explosive synchronization events. Here we provide a general framework for studying the effect of degree-frequency correlations on synchronization and study a class of correlations that displays remarkable dynamical properties. In particular, we find a family of correlations in which the synchronized state is (i) universal, i.e., the degree of synchrony is independent of network topology, and (ii) fully phase-locked, i.e., all oscillators become simultaneously phase-locked, despite having different frequencies. This family of correlations also separates two other classes of correlations with qualitatively different behaviors, for which either slow or fast oscillators remain drifting indefinitely. These results show that emergent collective behavior in networks of interacting dynamical systems can be made much more complex by simply creating correlations between the internal dynamic of each element and the structural properties of the network.

B38 - Dynamics of Human Walking and Factorized Poincare maps

Manoj Srinivasan, Yang Wang, The Ohio State University.

How do humans walk and run in a manner that they are stable and do not fall down? How do you quantify how stable a person is? While there are hundreds of mathematical models that can walk and run stably, their dynamics (in particular, responses to perturbations) have not been compared with corresponding human experiments.

In this talk, we will describe approaches to represent and infer the dynamics around apparently periodic motions and discuss specific results from analyzing human locomotion data. To represent the local dynamics, we elaborate on the concept of a "factorized Poincare map", which essentially consists of a large number of Poincare sections around the periodic orbit, and mappings of state and time from one section to the next. With sufficiently many Poincare sections, we can represent the local dynamics with great time resolution, and can compute derived quantities such as Phase Response Curves, local Isochrons, linear time-periodic ODEs. We describe methods to statistically infer a factorized Poincare map description when the nominal periodic motion is perturbed by incessant noise, and show how this representation can be used simulate responses to novel discrete perturbations. We will describe the results of these methods on application to long-time series human locomotion data. We will then comment on how the mathematical formalism of factorized Poincare maps may be used in the context of controlled dynamical system.

B39 - Generalized Local Induction Equation, Elliptic Asymptotics, and Simulating Superfluid Turbulence

Scott Strong, Lincoln D. Carr, *Colorado School of Mines*.

The asymptotic analysis of a vector field whose curl is ideally localized to an analytic curve presents an induced flow that is asymmetric in the local binormal direction. That is, a curved vortex displays autonomous dynamics. This result is typically known as the local induction approximation (LIA) and has an especially compact form for vortex arcs. Specifically, using the Biot-Savart integral one can recover an incompressible flow from a distribution of vorticity. If this distribution is an analytic curve then LIA is the lowest order approximation to the velocity field asymptotically close to the vortex curve. Approximation, in this case, speaks to truncation of the Taylor series representation of the vortex curve. Higher-order approximations are impeded by increasingly complicated integrations. However, analogous to mass-spring versus pendulum dynamics, these issues are mitigated by assuming a trigonometric parametrization of the vortex curve. This analysis yields a generalized induction equation (GIE), which provides an explicit representation of the velocity field in terms of elliptic integrals whose asymptotic forms are well understood. [1] Such a result is relevant the field of superfluidity where the model of a vortex curve is most appropriate. In this poster we discuss the asymptotics of GIE and illustrate its connections to the fluid dynamics of Bose-Einstein condensates, vortex filament methods and nonlinear partial differential equations with soliton solutions.

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B40 - Causality Inference beyond Granger Test and Transfer Entropy

Jie Sun, Erik M. Bollt, *Clarkson University*.

Inference of causality is central in nonlinear time series analysis and science in general. A popular approach to infer causality between two processes is to measure the information flow between them in terms of transfer entropy, a measure that is superior to the traditional Granger causality test. Using dynamics of coupled oscillator networks, we show that although transfer entropy can successfully detect the direction(s) of information flow between two coupled processes, it often results in erroneous identification of network connections under the presence of indirect influences, dominance of neighbors, or anticipatory couplings. To overcome these limitations, we develop a measure called causation entropy, and show that its application can lead to reliable identification of true couplings.

B41 - Large Systems of Interconnected Switches and Oscillators

Dane Taylor[1], Elana Fertig[2], Juan G. Restrepo[1], [1]*University of Colorado at Boulder,* [2] *Oncology Biostatistics, Johns Hopkins University*.

From biological systems such as the molecular regulation of metabolism and cell cycles to physical systems such as lasers, large networks of interacting dynamical systems are of widespread interest. While considerable progress has been made in the analyses of systems containing a single type of dynamical system (e.g., coupled oscillators and coupled switches), systems containing diverse components (e.g., both oscillators and switches) have received much less attention. We analyze large systems of interconnected oscillators and switches with positive feedback (i.e., oscillator synchronization promotes switches to turn on and switches enhance synchony when they turn on). Depending on the choice of parameters, we find coexisting stable solutions with (i) incoherent oscillators and all switches permanently off, (ii) synchronized oscillators and all switches permanently on, or (iii) synchronized oscillators and switches that periodically alternate between the on and off states. Our results are confirmed with numerical experiments exploring transitions between these steady state solutions, which we find can can be onset deterministically through dynamic bifurcations or spontaneously due to finite-size effects. Our results also suggest that heterogeneity may play an essential role in stabilizing the macroscopic dynamics of large, but finite-sized, complex systems.

B42 - Spontaneous Mode-selection on a Self-running Droplet Driven by Interfacial Instability

Fumi Takabatake[1], Nobuyuki Magome[2], Masatoshi Ichikawa[1], Kenichi Yoshikawa[3], [1]*Kyoto University,* [2]*Dokkyo Medical University,* [3]*Doshisha University*.

Currently, spontaneous motions of liquid droplets, solid particles and gels under non-equilibrium conditions have been actively investigated [1]. Among the phenomena of spontaneous motions, self-agitation of a fluid interface has been well utilized especially in that field so called chemical Marangoni effect. The chemical Marangoni effect is induced by local variations in interfacial tension, which are caused by a chemical concentration gradient, to transduce the chemical concentration variation into transportation of the fluid in the interface under isothermal condition. Recently, it has been revealed that irregular interfacial agitation caused by the Marangoni instability is spontaneously converted into a regular motion with a specific mode by choosing a suitable boundary condition, e.g., internal or external asymmetry. In the present paper, we report that a solid/liquid composite having the anterior-posterior asymmetry exhibits various modes of regular spontaneous motion driven by chemical Marangoni effect [2]. When an oil droplet of oleic acid attached to a solid sodium oleate is placed on a water phase, the composite undergoes specific spontaneous motion, such as translational motion, spinning motion and orbital motion. The results showed that the composite assumes a certain mode of spontaneous motion depending on the relative size of the solid sodium oleate with respect to that of the oil droplet, i.e., the degree of driving force or non-equilibricity. The essential features of above mode switching are reproduced by using ordinary differential equations by taking into account of the spontaneous symmetry breaking on geometry of the composite under a thermodynamically dissipative condition.

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B43 - Stability and Clustering of Self-similar Solutions of Aggregation Equations

Hui Sun, David Uminsky, Andrea Bertozzi, *University of California Los Angeles*.

We consider the linear stability of a family of exact collapsing similarity solutions to the aggregation equation in a general dimension, where the density has a power law interaction with the exponent γ. It was previously observed that radially symmetric solutions are attracted to a self-similar collapsing shell profile in infinite time for $\gamma > 2$. We compute the stability of the similarity solution and show that the collapsing shell solution is stable for $2 < \gamma < 4$. For $\gamma > 4$, we show that the shell solution is always unstable and destabilizes into clusters that form a simplex which we observe to be the long time attractor. We then classify the stability of these simplex solutions and prove that two-dimensional (in-)stability implies n-dimensional (in-)stability.

B44 - Simulating Ginzburg Landau Dynamics with Efficient Spectral Galerkin Methods

Ty Thompson, *Colorado School of Mines*.

In this research, we focus on the efficient numerical simulation of nondeterministic critical phenomena in the Ginzburg Landau (GL) model for superconductivity. Deterministic versions of the GL model have been widely used to study dense vortex configurations in thin superconductors immersed in an externally applied magnetic field. Soon after the inception of the model, a complete microscopic analysis qualifying its accuracy in a baseline case was found. More recently, measurements of vortex arrangements consistent with GL predictions have emerged in the literature. However, our understanding of how vortex configurations evolve in time remains somewhat incomplete, particularly when the associated dynamics are essentially nondeterministic. The Langevin extension of the time dependent GL equations provides a natural phenomenological context for the modeling of such dynamics in symmetric superconductors, but its stochastic nature makes computational efficiency a primary challenge.

Our numerical investigations are performed on 2-manifolds, with rotational symmetry about the axis of a constant magnetic field, and we work from the ideal (superconductor or normal) initial states. We first qualify the use of the stochastic GL extension with some symmetry arguments and supporting numerical evidence.

Then, we introduce a perturbation approach that allows us to simulate the formation of various dense, stable vortex configurations without the formal introduction of randomized forcing. Lastly, we proceed with exhaustive stochastic simulations using methods built from our most efficient deterministic techniques. Owed to the nature of our chosen problem and context, a fully discrete spectral Galerkin method is not prohibitive to implement. To maximize efficiency and our parallel implementation options, without imposing a priori assumptions regarding the stochastic nature of the unknown, we use a generalized spectral decomposition (GSD) for the fully discrete solution to achieve a reduction in dimensionality. Some results of exhaustive stochastic simulations, and our efforts in qualifying highly efficient perturbation approaches, will be discussed.

B45 - Experimental Chimeras: the Broken Symphony of Metronome Swing States

Shashi Thutupalli[1,3], Erik A. Martens [1,2], A. Fourriere[1], O. Hallatschek[1], [1]*Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany,* [2]*Technical University of Denmark,* [3]*Princeton University*.

About ten years ago, a peculiar state was predicted by Kuramoto and his co-workers: they studied a network of nonlocally coupled oscillators, i.e., oscillators that are coupled with a strength attenuating with distance, and discovered a state where synchronous and asynchronous oscillators co-exist, even though the oscillators are identical. Due to its incongruous nature, this surprising phenomenon was later dubbed as a chimera state, alluding to the ancient Greek monster with the same name. Since then, numerous theoretical studies have been carried out to study the emergence of this state in various network topologies, different oscillator systems, its stability and bifurcation behavior. Here, we use a purely mechanical system of coupled metronomes to show that chimeras emerge naturally from a competition between two antagonistic synchronization patterns. Our setup mimics the topology studied previously by Abrams et al. and Laing, where each population of oscillators is strongly coupled with itself, but with lesser strength with the neighboring population (thus constituting the simplest discretized version of nonlocal coupling). By variation of the oscillation frequency and the inter-population coupling strength, we establish a phase diagram for chimeras. We obtain a spectrum of complex states, encompassing and extending the set of previously described chimeras. Further, we compare our experimental results with a mathematical model, which allows to study the nature of the chimera state in a physical context and is analyzed in more detail. Our mechanical model strongly suggests that such states are a ubiquitous feature in nature, manifesting themselves in technological settings ranging from power grids to optomechanical arrays.

B46 - Phase Transitions in the Quadratic Contact Process on Complex Networks

Chris Varghese, Rick Durrett, *Duke University*.

The linear contact process is a well studied model for the spread of infections. Here, a single infected (1) individual can infect a susceptible (0) individual, and infected individuals are allowed to recover ($1 \to 0$). A natural extension of this model is the *quadratic contact process* (QCP) where a combination of two 1s is required to effect a $0 \to 1$ change. To date, the QCP has only been studied on low dimensional lattices, mainly as a model for autocatalytic chemical reactions. However, the QCP on complex networks can capture some of the essential features of population change in a species via sexual reproduction and death. We define two versions of the QCP – *vertex centered* (VQCP) and *edge centered* (EQCP). In these versions, the birth events are $1{-}0{-}1 \to 1{-}1{-}1$ and $1{-}1{-}0 \to 1{-}1{-}1$ respectively where - represents an edge and 1 (0) stands for an occupied (empty) vertex. To understand the effects of degree distribution, we investigate the QCP on regular, Erdős-Rényi and power law random graphs. We perform mean field calculations as well as simulations to find the steady state fraction of occupied vertices as a function of the birth rate. We find that on the homogeneous graphs (regular and Erdős-Rényi) there is a discontinuous phase transition with a region of bistability, whereas on the heavy tailed power law graph, the transition is continuous. The critical birth rate is found to be positive in the former but zero in the latter. It is interesting to note that while the transitions of the VQCP and the EQCP are different on low dimensional lattices, they are similar on the complex networks considered.

B47 - Noise-induced Oscillations in Network Motifs of Non-linear Oscillators with Delay

Andrea Vullings[1], Valentin Flunkert[2], Eckehard Schöll[1], [1]*Technische Universität Berlin,* [2]*Germany, IFISC, Palma de Mallorca, Spain*.

We investigate noise-induced oscillations of network motifs composed of non-linear oscillators (super- or subcritical Hopf-normal forms), which are paradigmatic for neural networks and coupled semiconductor lasers. Fluctuations are modeled by Gaussian white noise, and finite signal propagation velocities are accounted for by a time-delayed coupling. Using a self-consistent mean-field approach, we study stochastic synchronization and compare our results with numerical simulations. We find that the delay can enhance or destroy the collective oscillations in a network motif depending upon the delay time. For the supercritical case with nonzero amplitude-phase coupling (corresponds to the linewidth enhancement factor in semiconductor-laser physics) a noise-induced frequency shift of the oscillations is observed. In the case of noisy subcritical Hopf-normal forms we observe coherence resonance. We study numerically the effect of the time delay on the optimal noise strength in the coupled system.

B48 - Dynamics of the Leaky Integrate-and-Fire Neuron with Inhibitory Feedback

Richard Watson, James Crutchfield, *University of California, Davis*.

The relationship between patterns of neural spikes (the format of communication and computation in the brain) and the anatomical configurations that produce them is fundamental to understanding how brains work. Feedback inhibition circuits are a specific variety of neural connectivity which are statistically overrepresented throughout the brain in a range of species. What functional characteristics are typical of these subsystems such that their role would be deemed so basically important by evolution?

We analytically studied a simple model, the Leaky Integrate-and-Fire (LIF) model neuron with an inhibitory autapse (i.e. synapse onto self), to elucidate this question. Here we describe new results linking structural parameters of the neural circuit to changes in its behavioral dynamics and ultimately in its patterns of spiking.

Neurons in isolation are incapable of introducing dependency in the sequence of interspike intervals (ISIs) they emit. However, in the system we study the autapse causally impacts the neuron at a future time. Here we examine analytically the dynamics underlying the dependency structure of sequences of ISIs in this system. In some common behavioral regimes, the dynamics limit the ISI dependency to Markov order one. In these cases we are able to explore the behavior with a 1D return map. However, if the autapse delay is long enough or the input is strong enough, Markov order increases and additional dimensions are necessary to explain the more complex behavior.

We use computational mechanics [1] to further dissect the behavioral character of the LIF model neuron with feedback inhibition for arbitrary orders of dependence. We find that the underlying states of the system are arranged in layers, where outer layers are only visitable from one layer beneath. Each layer of states, made available by longer autapse delays or stronger input, introduces a boost in memory to the system. As memory grows larger, the system is capable of storing more information related to input.

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B49 - Partial Control of Chaos and Continuity of Safe Sets

Genming Wang, Yuzuru Sato, *RIES/Dept. of Mathematics, Hokkaido University*.

Since the theory of controlling chaos proposed more than two decades ago [1][2], it has been applied to various nonlinear systems. Recently, Zambrano, Sanjuan, and Yorke have studied a new problem on "loose control" of chaotic dynamical systems, which is called partial control of chaos [3][4]. An open dynamical system with presence of noise is controlled by a carefully chosen perturbation to trap an orbit in a finitely bounded region forever. It can be done by control signals smaller than the amplitude of noise. The set of partially controllable initial conditions is called safe set [4], which can be constructed by using Sculpting algorithm [5]. In this presentation, we investigate the simplest problem of the partial control, that is, safe sets of one-dimensional maps with and without escapes. We find that the safe set will not always grow continuously by increasing control signals, and disappears with some amplitude of noise no matter how large control signals are.

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B50 - Damped Oscillations in the Ratios of Stock Market Indices

Ming-Chya Wu, *Research Center for Adaptive Data Analysis, National Central University, Taiwan*.

A stock market index is an average of a group of stock prices with weights. Different stock market indices derived from various combinations of stocks may share similar trends in certain periods, while it is not expected that there are fixed relations among them. Here we report our investigations on the daily index data of Dow Jones Industry Average (DJIA), NASDAQ, and S&P500 from 1971/02/05 to 2011/06/30. By analyzing the index ratios using the empirical mode decomposition, we find that the ratios NASDAQ/DJIA and S&500/DJIA, normalized to 1971/02/05, approached and then retained the values of 2 and 1, respectively. The temporal variations of the ratios consist of global trends and oscillatory components including a damped oscillation in 8-year cycle and damping factors of 7183 days (NASDAQ/DJIA) and 138471 days (S&P500/DJIA). Anomalies in the ratios, corresponding to significant increases and decreases of indices, only appear in the time scale less than an 8-year cycle. Detrended fluctuation analysis and multiscale entropy analysis of the components with cycles less than a half-year manifest a behavior of self-adjustment in the ratios, and the behavior in S&500/DJIA is more significant than in NASDAQ/DJIA.

B51 - Testing the Predictions of Random Matrix Theory in Low Loss Wave Chaotic Scattering Systems

Jen-Hao Yeh, Thomas M. Antonsen, Edward Ott, and Steven M. Anlage, *University of Maryland*.

Random matrix theory (RMT) has been successfully applied to predict statistics of wave properties in complicated wave scattering systems. The field is known as quantum chaos or wave chaos. The RMT predictions demonstrate that the distributions of these universal wave properties only depend on the loss parameter of the system and basic physical symmetries, falling mainly in to the Gaussian Orthogonal Ensemble (GOE) or the Gaussian Unitary Ensemble (GUE) classes. Examination of these predictions in very low loss systems is interesting because extreme limits for the distribution functions and other predictions are encountered. Therefore, we use a wave-chaotic superconducting cavity to establish a low loss environment and test RMT predictions, including the statistics of the scattering (S) matrix and the impedance (Z) matrix, the universality (or lack thereof) of the Z- and S-variance ratios, and the statistics of the proper delay times of the Wigner-Smith time-delay matrix. The results also demonstrate that the number of eigenmodes accessible in the experiment is extremely critical for detailed comparison to theory in the low loss limit. Our experimental results of different properties agree with the RMT predictions.

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B52 - Hydrodynamic Fluctuations and Shear Viscosity in the Unitary Fermi Gas

Ryan Young, Paul Romatschke, *University of Colorado at Boulder*.

Hydrodynamics predicts perdurable shear and sound waves. Thermal fluctuations within these waves can dissipate momentum, contributing to the shear viscosity and other transport coefficients. Using the equation of state for a unitary Fermi gas from a recent MIT experiment, we find lower bounds for the viscosities η/n and η/s as a function of temperature. These results are compared to the quantum Monte Carlo results from Wlazlowki et al, $\eta/n \leq 0.2$, and Chafin and Schafer, $\eta/n \geq 0.3$. A possible resolution to the discrepancy is found in a reanalysis of the shear viscosity spectral function.

B53 - Learning Cycles in Hopfield-type Networks with Delayed Coupling

Chuan Zhang, Gerhard Dangelmayr, Iuliana Oprea, *Colorado State University*.

Cyclic patterns of neuronal activity are ubiquitous in neural systems of almost all animal species. To elucidate the underlying dynamical mechanisms for the storage and retrieval of cyclic patterns in neural networks is fundamentally important for understanding the origin of rhythmic movements. In this presentation, we summarize our investigations in the storage and retrieval of binary cyclic patterns in continuous, asymmetric Hopfield-type networks with delayed coupling using the pseudoinverse learning rule. The presentation is organized into three parts. First, we show that all cyclic patterns satisfying the transition conditions can be successfully stored and retrieved, and the cyclic patterns satisfying the same transition condition can be stored in the same network, and retrieved with appropriately selected initial conditions. Next, we show how the subspace structures of the vector space spanned by the row vectors of the cyclic patterns determine the topology of the networks constructed from these cyclic patterns. Last, we show that transitions from fixed points to attracting limit cycles (cyclic patterns) are multiple saddle-node bifurcations on limit cycles.

B54 - Direct observation of Kelvin waves excited by quantized vortex reconnection

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Quantized vortices are key features of quantum fluids such as su- perfluid helium and Bose-Einstein condensates. The reconnection of quantized vortices and subsequent emission of Kelvin waves along the vortices are thought to be central to dissipation in such systems. By visualizing the motion of sub-micron particles dispersed in super- fluid 4 He, we have directly observed for the first time the emission of Kelvin waves from quantized vortex reconnection. We characterize one event in detail, using dimensionless similarity coordinates, and compare with several theories. Finally, we give evidence for other examples of wavelike behavior in our system.