Dynamics Days US 2014

Georgia Institute of Technology, Jan. 2 – 5, 2014

Book of Abstracts

January 4, 2014.

Welcome to DYNAMICS DAYS US 2014!

We are looking forward to talks, poster presentations, and discussions over the entire span of fields of dynamics and nonlinearity. For over thirty years, the Dynamics Days conferences have been a forum for presenting the latest developments on all matters nonlinear. Initiated by Robert H. G. Helleman in the mists of time, this is the 33rd US meeting, and there have been 34 European (with sometimes over 500 participants!), 8 Asia-Pacific, and 2 South American sister conferences so far. They have all been truly multidisciplinary from the very beginning, changing apace with the progress in the vast field of problems where nonlinearities play a key role, and so is this year's conference. We are proud to host participants from across the globe, representing a vast range of disciplines. We look forward to learning about exciting cutting edge developments, and hope that this meeting stimulates many new cross-disciplinary collaborations.

We are most grateful to everybody who helped in organizing the conference. In particular, we would like to thank many colleagues for their help and advice; Bernhard Mehlig (DDays EU 2012) for providing us with mailing lists and the abstracts book design, Juan G. Restrepo (DDays US 2013) for sharing the organizational correspondence with us, Irene Sendiña Nadal for passing on the (DDays EU 2013) web pages to us, Sneha Bishnoi for adopting the Madrid conference web pages to the Atlanta conference, David Hu for designing the conference poster, Darryl Warsham for helping us in all matters financial, Annette Rohrs for sage advice, the School of Physics administrative staff team - Jan Brown, Keia Dodd, Ashley Jeter, Alison Morain, Nicole Thompson and the student helpers for being the boots on the ground.

We are grateful to our sponsors for making this meeting possible: the National Science Foundation, the Burroughs-Wellcome Fund, the APS Group for Nonlinear and Statistical Physics, AIP Publishing, Elsevier, Springer, and Georgia Tech's College of Sciences, College of Engineering, and School of Physics.

Wishing you all a good conference,

Roman Grigoriev
on behalf of the organizing committee.

The program and the abstracts

The printed conference program will be distributed to participants (a copy is also available on the conference web page). This booklet, available on the conference web page as a hyperlinked PDF document, lists all talks and posters, each part ordered alphabetically.

All **talks** will be held in the Clough Undergraduate Learning Commons, Room 152.

The **posters** are ordered alphabetically by the name of the presenting author. The **poster** number indicates the number of the poster board, the first half presented in the first posters session, and the second half in the second poster session.

Escapes

There is a Starbucks cafe at the the far end of the Clough building (closed Saturday), the student center across the quad, and a number of affordable eateries across the 5th Street bridge (the free yellow Tech Trolley runs from the Skiles building stop). The High Museum of Art is a 1/2 hour walk.

For the fearless, we plan a GA Tech climbing wall expedition from 7pm to 10pm on Friday, Jan. 3. We will meet in Clough at 6:40pm to walk over to the Campus Recreation Center as a group.

Whereto next?

Dynamics Days EU 2014 will take place in Beyreuth, Germany, September 8-12, 2014. "Nonlinear dynamics and stochastic methods: From neuroscience to other biological applications", March 10-12, 2014, and 9th Intl. Summer School/Conference "Let's face chaos through nonlinear dynamics", 22 June - 6 July 2014, might also be of interest.

Contents

Part I

Conference Talks

Growth and instability of the liquid rim in the crown splash regime

Gbemeho Gilou Agbaglah and Robert Deegan

University of Michigan

We study the time expansion of the leading edge of the emerged sheet after the impact of a drop onto a thin liquid film in the crown splash regime. By performing numerical simulations, which are qualitatively and quantitatively in a good agreement with the experiment results [1], we show that the liquid rim formed at the free end of the crown grows linearly in time.

Then using our previous linear theory [2], combined with the present simulations, we show that the instability of the rim is driven by the Rayleigh-Plateau mechanism. The Rayleigh-Taylor instability, due to the rim deceleration, amplifies the interface corrugations but does not lead to a change of the number of spikes.

Finally, the number of secondary droplets is predicted based on this linear theory and the simulations.

References

1. L. V. Zhang, P. Brunet, J. Eggers, and R. D. Deegan. Wavelength selection in the crown splash. Phys. Fluids 22: 122105, 2010.
2. G. Agbaglah, C. Josserand, and S. Zaleski. Longitudinal instability of a liquid rim. Phys. Fluids 25: 022103, 2013.

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Lagrangian coordinates for the mass points of planar Burgers equation

Maxim Arnold, Yulij Baryshnikov and Yuriy Mileyko

University of Illinois

The solution of d-dimensional Burgers equation with generic initial data develops a finite-time singularity. However it is possible to define a generalized solution below that critical time and define the velocity field inside the instant shock formed by a singularity. Set of all instant shocks forms a d-dimensional stratified space in the $d + 1$ dimensional extended phase space and is called world shock. Thus generalized solution of Burgers equation defines a flow on world shock.

We geometrically characterize the pre-images of the points in the world shock for the planar Burgers equation and present a classification of mass distribution under possible bifurcations of the instant shocks.

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Living liquid crystals

Igor Aronson, Andrey Sokolov, Shuang Zhou and Oleg Lavrentovich

Argonne National Laboratory

Placement of swimming bacteria in lyotropic liquid crystal, a water dispersion of elongated aggregates of organic molecules, produces a new class of biomechanical systems - living liquid crystal - LLC. This new hybrid material synergistically combines the properties of both constituents: biological response to external stimuli and long-range order due to anisotropy. LLC displays a wide range of fundamentally new phenomena, from the emergence of self-organized textures caused by bacterial swimming to direct optical visualization of flagella rotation and the liquid crystal-controlled trajectories of bacterial motion. LLC sheds new light on self-organization in active biomechanical systems and can possibly lead to valuable biomedical applications.

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Protection against multistability in a half-center oscillator

William Barnett and Gennady Cymbalyuk

Georgia State University

Oscillatory pairs of mutually inhibitory neurons, half-center oscillators (HCOs), represent a common motif of connectivity in central pattern generators (CPGs). In ganglia 3 and 4 of the medicinal leech, HCOs form the kernel of the heartbeat CPG. Each HCO is composed of endogenously bursting interneurons. Previously, a biophysically accurate model of this HCO has been developed. Bistability of bursting and silence has been shown in this canonical model. The canonical model has been extended to a database that describes a family of models in which bistability is highly prevalent. Given that the coexistence of bursting and silence could present a life threatening condition for the leech, these results are surprising. We investigated perturbations that switched the activity of single HNs and the HCO from bursting to silence. A perturbation was induced by single square pulses of current characterized by amplitude and phase of application. Over a series of simulations, we systematically varied these parameters and acquired a set of values for phase and amplitude for which a switch was triggered. In the canonical model of a single HN for which the value of the leak conductance was 9.59 nS, 15.4of pulses triggered a switch. However, the susceptibility of the model was drastically reduced such that only 1.5in the HCO network. In conclusion, we find that this motif brings robustness despite unreliability in its components.

This research was supported by NSF grant PHY-0750456.

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Localized convection in a rotating system

Cedric Beaume, Hsien Ching Kao, Edgar Knobloch and Alain Bergeon

UC Berkeley

We study two-dimensional spatially localized convection in a horizontal fluid layer rotating around the vertical and heated from below [1]. With stress-free boundary conditions stationary spatially localized convection is present [2]. These states are embedded in a background shear layer and lie on a pair of intertwined solution branches exhibiting “slanted snaking” [3]. Similar solutions with no-slip boundary conditions are no longer embedded in a background shear and exhibit standard snaking, i.e. snaking without a slant. These solutions may be stable [4]. Homotopic continuation from free-slip to no-slip boundary conditions is used to track the changes in the properties of the solutions and the associated bifurcation diagrams. An explanation of the results is given.

References

1. G. Veronis, *J. Fluid Mech.* **5**, 401–435 (1959)
2. C. Beaume, A. Bergeon, H.-C. Kao, E. Knobloch, *J. Fluid Mech.* **717**, 417–448 (2013)
3. J. Dawes, *SIAM J. Appl. Dyn. Syst.* **7**, 186–206 (2008)
4. C. Beaume, H.-C. Kao, E. Knobloch, A. Bergeon, *submitted*

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Multistable randomly switching dynamical networks: The odds of meeting a ghost

Igor Belykh

Georgia State University

In many biological and man-made networks the coupling strength or the connection topology can vary in time, according to a stochastic dynamical rule. This talk focuses on mathematical analysis and modeling of dynamical systems and networks whose coupling or internal parameters stochastically switch on and off. We study dynamical properties of switching networks as a function of the switching frequency. If random switching is fast compared to the oscillator's intrinsic time scale, one expects the switching system to follow the averaged system, obtained by replacing the random variables with their mean. If the averaged network is multistable and one of its attractors is not shared by the switching network, then it acts as a ghost attractor for the switching network. We derive explicit bounds that connect the probability of converging towards the ghost attractor, the switching frequency, and the chosen initial conditions.

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Finite-amplitude thresholds for transition in Taylor-Couette flow

Daniel Borrero, Samuel G Raben and Michael F Schatz

Georgia Institute of Technology

We present the results of an ongoing experimental study of the finite-amplitude thresholds for transition to turbulence in Taylor-Couette flow when only the outer cylinder is allowed to rotate. In this regime, the centrifugal effects that drive the famous transition to turbulence via successive flow instabilities are suppressed and the laminar state is predicted to be stable to infinitesimal perturbations at all Reynolds numbers. However, if a *sufficiently* large finite-amplitude perturbation is applied to the flow, it can undergo a direct transition to turbulence. We perturb the flow by injecting small amounts of fluid from holes on the inner cylinder wall and use this to determine the critical amplitude required to cause transition. We study how this critical amplitude scales with Reynolds number for systems of different aspect ratios (i.e., axial extent of the system normalized by the size of the gap between the cylinders).

8

Submesoscale dynamics in the Gulf of Mexico

Annalisa Bracco

Georgia Tech

We provide an overview of the fluid dynamical processes at play in the ocean at scales of O(1) km, the so called submesoscales. The submesoscales represent the transition scale between non-local and local dynamics in the ocean and the characterization of their turbulent motions, together with their impact on the overall oceanic energy budget, is an active area of research in physical oceanography.

Our overview will make use of a suite of numerical simulations performed for the Gulf of Mexico. The Gulf is suitable for our interests because populated by mesoscale - O(10) to O(100) km - vortices, the Loop Current eddies, with typical diameter of 200 km, and by smaller frontal structures and vortices. It provides, therefore, an ideal location for investigating the interactions between local and non-local processes at different time and space scales. The simulations are performed using ROMS, the Regional Ocean Modeling System, and the horizontal resolution varies from 1 to 5 km. We present both Eulerian and Lagrangian passive tracer experiments. Our focus is on the role played by submesoscale dynamics in the transport and mixing throughout the water column, above and below the mixed layer.

We find a significant increase in amplitude of the modeled vertical velocities for increasing horizontal resolution through the whole water column. In our simulations, the distributions of vertical velocity w do not change in shape, but are resolution dependent in their variance, and the representation of the energy content of w is affected by the model resolution at all frequencies. The instantaneous values of the modeled w can reach several tens of m/day (up to 80 m/day). Those high values are not associated with significantly higher level of vertical diffusion (numerical and due to vertical mixing parameterization), but to different transport processes. Even higher values have been found in moored ADCP measurements in correspondence with the passage of Loop Current Eddies in the Gulf of Mexico.

We conclude that processes at the submesoscale are fundamental in driving vertical transport in eddy dominated flows, both within and below the mixed layer, and we discuss the potential implications of our results for the broad climate modeling community.

Acknowledgment: This work was supported by a grant (in part) from BP/the Gulf of Mexico Research Initiative to support consortium research entitled "Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG)," administered by the University of Mississippi, GRIID: R1.x132.141:0001 and by the National Science Foundation (OCE-0928495).

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Electron dynamics in atoms subjected to intense laser pulses

Cristel Chandre

CNRS

In this talk I will show how nonlinear dynamics is able to shed new light on laser-matter interaction and strong field physics at the attosecond time scale.

The advent of powerful and short laser pulses heralded a new era in atomic and molecular physics about three decades ago. Irradiating targets such as atoms or biological complexes with such intense laser pulses has become the tool of choice for resolving the structure of matter at unprecedented spatial and temporal scales. About twenty years ago, the theoretical framework for such processes was established and remains the state-of-the-art in strong field physics: It centers on the recollision model: Electrons are first detached (presumably by tunneling) and absorb energy while following the laser, only to be hurled back at the ionic core when the laser reverses direction where they can ionize more electrons or generate very high harmonics of the driving laser by high harmonic generation. This recollision scenario omits the ion's Coulomb potential after tunneling. One decisive success of the recollision model is the theoretical prediction of the highest harmonic generated during this recombination process (the so-called high harmonic cut-off). In reality, the Coulomb interaction cannot be neglected, even after tunneling, since it drives all kinds of intense-laser phenomena. In this talk, I will show how nonlinear dynamics is able to resolve this paradox by building a purely classical recollision scenario which fully incorporates the Coulomb interaction at every stage of the recollision process [1]. I will highlight the key role played by a special class of periodic orbits, called recolliding periodic orbits [2], allowing for recollisions to occur and explaining the high harmonic cut-off.

References

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2. A. Kamor, F. Mauger, C. Chandre, T. Uzer, *Phys. Rev. Lett.* **110** 253002 (2013).

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Delay-differential equations in models of cardiac myocytes: An alternative mechanism for alternans

Elizabeth Cherry

Rochester Institute of Technology

In the heart, period-2 behavior of electrical responses (action potentials, APs), referred to as alternans, is known to give rise to more complicated arrhythmias like fibrillation. Alternans can result from a number of different mechanisms, including a strong adaptation to electrical stimulation rate (steep AP duration restitution curve), intracellular calcium dynamics, and scenarios such as heterogeneity of intrinsic electrical properties, certain spiral wave trajectories, and a non-monotonic conduction velocity restitution relation. Mathematically, all these mechanisms can be generated from nonlinear systems of coupled ordinary and/or partial differential equations. An alternative approach is to consider the use of delay-differential equations, which are known to promote complex dynamics in a number of different settings. Delays may arise naturally in multiple cellular processes involving non-instantaneous events, such as ion channel gating and intracellular calcium cycling. We introduce delay-differential equations in the context of cardiac cells. Then we compare the alternans induced by the alternative delay-differential equation formalism with alternans arising from more widely used ODE/PDE-based mathematical formulations. We analyze the dynamical behaviors of the system, including higher-order periodicities and chaos, and discuss the implications of our findings.

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Exactly solvable chaos in an electromechanical oscillator

Ned Corron, Benjamin A. M. Owens, Mark T. Stahl, Jonathan N. Blakely and Lucas Illing

US Army

A novel electromechanical chaotic oscillator is described that admits an exact analytic solution. The oscillator is a hybrid dynamical system with governing equations that include a linear second order ordinary differential equation with negative damping and a discrete switching condition that controls the oscillatory fixed point. The system produces provably chaotic oscillations with a topological structure similar to either the Lorenz butterfly or Rossler's folded-band oscillator depending on the configuration. Exact solutions are written as a linear convolution of a fixed basis pulse and a sequence of discrete symbols. We find close agreement between the exact analytical solutions and the physical oscillations. Waveform return maps for both configurations show equivalence to either a shift map or tent map, proving the chaotic nature of the oscillations.

References

1. Owens, B. A., Stahl, M. T., Corron, N. J., Blakely, J. N., and Illing, L., Exactly solvable chaos in an electromechanical oscillator. *Chaos* **23**, 033109 (2013).

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Mutually opposing forces during locomotion can eliminate the tradeoff between maneuverability and stability

Noah Cowan, Shahin Sefati, Izaak Neveln, Eatai Roth, Terence Mitchell, James Snyder, Malcolm MacIver and Eric Fortu

Johns Hopkins University

A surprising feature of animal locomotion is that organisms typically produce substantial forces in directions other than what is necessary to move the animal through its environment, such as perpendicular to, or counter to, the direction of travel. The effect of these forces has been difficult to observe because they are often mutually opposing and therefore cancel out. Indeed, it is likely that these forces do not contribute directly to movement but may serve an equally important role: to simplify and enhance the control of locomotion. To test this hypothesis, we examined a well-suited model system, the glass knifefish Eigenmannia virescens, which produces mutually opposing forces during a hovering behavior that is analogous to a hummingbird feeding from a moving flower. Our results and analyses, which include kinematic data from the fish, a mathematical model of its swimming dynamics, and experiments with a biomimetic robot, demonstrate that the production and differential control of mutually opposing forces is a strategy that generates passive stabilization while simultaneously enhancing maneuverability. Mutually opposing forces during locomotion are widespread across animal taxa, and these results indicate that such forces can eliminate the tradeoff between stability and maneuverability, thereby simplifying neural control.

References

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Criticality and information flow in an adaptive system

Bryan Daniels, David Krakauer and Jessica Flack

University of Wisconsin, Madison

In physical systems, boundaries in parameter space that separate different large-scale behavior correspond to phase transitions, where small changes in microscopic parameters lead to drastic changes in macroscopic observables. We use fine-grained data about conflict in a macaque society to ask whether this social system is located near a phase transition. We find using two models (an equilibrium Ising model and a dynamic branching process model) that the system is near but below a transition, indicating that aggression dissipates quickly enough to avoid becoming typically widespread, but not so quickly that large fights are impossible. A relation between thermodynamics and information theory shows that being near the transition implies that it is easier for an observer of fight sizes to infer changes in individual proclivities to fight. More generally, this points to the possibility of quantifying a system's collective behavior by measuring the degree to which information can percolate among different spatial scales.

References

1. Daniels, Bryan C. and Krakauer, David C. and Flack, Jessica C.. Sparse code of conflict in a primate society. Proceedings of the National Academy of Sciences 109: 14259-14264, 2013. doi 10.1073/pnas.1203021109.

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Renormalization group for quantum walks

Stefan Falkner, Stefan Boettcher and Renato Portugal

Emory University

Quantum walks are not only a quantum mechanical extension of the random walk, but have been used to study quantum transport phenomena and to devise quantum search algorithms [2]. Even general quantum computation can be formulated as a quantum walk [1]. Nevertheless, the general understanding of quantum walks and how quantum interference and unitarity influence the time evolution is limited. So far, only translational invariant lattices allow analytical insights into the rich behavior that quantum walks exhibit. Numerical simulations show interesting phenomena (localization, interference), but do not reveal the underlying reasons or make predictions that can be tested.

We propose a Renormalization Group treatment of quantum walks on self-similar graphs. The recursion equations we find can be interpreted as a high dimensional dynamical system with fixed points, but also chaotic regimes. For the classical random walk, fixed points characterize the long time behavior, whereas the chaotic parts have to be examined to extract properties of the quantum walk. Studying the equations with methods from dynamical systems using, e.g., Lyapunov exponents, we connect properties of the mapping to the quantum walk, and hence make prediction of its behavior. By applying our method to the dual Sierpinsky gasket, we observe a novel situation, where the quantum walk spreads faster than the corresponding random walk, but gets completely localized in the large system limit.

References

1. N. B. Lovett, et al., *Phys. Rev. A* **81** (2010)
2. J. Kempe, *Contemp. Phys.* **44** (2003)

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Evolution and robustness in genetic networks

Leon Glass

McGill University, Montreal

Genetic activity is partially regulated by a complicated network of proteins called transcription factors. I will describe a mathematical framework to relate the structure and dynamics of these genetic networks. The underlying idea is to capture the topology and logic of the network interactions by a Boolean network, and to then embed the logical network into continuous piecewise linear differential equations. The equations can be analyzed using methods from discrete mathematics and nonlinear dynamics. By changing the logical structure randomly, it is possible to evolve the networks in an effort to identify networks that display rare dynamics - e.g. networks with long stable cycles or with a high level of topological entropy. I also consider the concept of robustness in the context of these equations and argue that robustness should be a key feature of genetic networks underlying important biological functions.

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Whirling skirts and metrically constrained dynamics

James Hanna, Jemal Guven and Martin Michael Mueller

Virginia Tech

Steady dihedral patterns, consisting of sharply peaked traveling waves, may be observed on a spinning skirt. These features also arise in a minimal model of the inertial dynamics of a conically symmetric sheet subject to a constraint on its two-dimensional metric. The symmetry of the sheet admits a flow, with associated Coriolis forces that play an essential role in establishing the patterns.

Mutation of the Franck-Condon state into embryonic nuclei at the earliest stage of photoinduced nucleation

Kunio Ishida and Keiichiro Nasu

Toshiba Corporation

Recent theoretical and experimental studies on photoinduced cooperative phenomena have shown that relaxation dynamics of the Franck-Condon state is a key to understand the initial process accompanied by nucleation. In order to clarify its dynamical properties in microscopic scale, we have employed a model of localized electrons coupled with optical phonons, which has been shown to be suitable for studying photoinduced structural change in ultrashort time scale [1].

In the present study, we focus on the time evolution of boundary properties of photoinduced nuclei in order to enable quantitative study of the mutation of the Franck-Condon state into embryonic nuclei at the earliest stage of the nucleation process. By regarding the spatial distribution of the excited electronic state population as a geometric pattern, we applied the multifractal analysis to it and calculated the temporal behavior of the fractal dimension $f(\alpha)$ as a function of the Lipschitz-Hölder exponent α which is an appropriate method for understanding the nonlinear relaxation process of the nucleation [2].

We found that the incubation period observed in various types of photoinduced cooperative phenomena corresponds to the formation of embryonic nuclei which is driven by the repetition of nonadiabatic/adiabatic transition between electronic states during the relaxation of the Franck-Condon state. The multifractal analysis on the spatial patterns is shown to be quite effective to understand this feature, and we show that the present study opens up a possibility to reveal the physics of the earliest stage of the photoinduced nucleation by spectroscopic techniques.

References

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Periodic windows within windows within windows

Madhura Joglekar and James Yorke

Univ of Maryland, College Park

For a dynamical system $X_{n+1} = F(C, X_n)$, there are often infinitely many periodic windows, that is, intervals in the parameter C in which there is stable periodic behavior. The windows display a fractal structure, wherein each window has windows of higher orders. Fortunately there is one situation where these nested windows can be studied effectively, the quadratic map $X_{n+1} = C - X_n^2$. For a given small $\epsilon > 0$, we say C is ϵ-uncertain if there is a periodic attractor for exactly one of the values C and $C + \epsilon$. The other presumably has chaotic behavior. We find that for ϵ very small, for the great majority of ϵ-uncertain pairs, one of the two parameters is in a very high order window, that is, a window within a window within a window ... N times for large N.

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From fish swimming to cell motility

Eva Kanso

Aerospace and Mechanical Engineering, University of Southern California

I will present a family of dipole models that capture the far-field hydrodynamic effects of self-propelled bodies. These models can be viewed as leading-order approximations for studying the hydrodynamic interactions in (1) schools of fish and (2) populations of cells in confined geometries. I will particularly discuss motion stability and comment on the insights we obtain in the context of fish schooling and in the emergence of global structures in cell populations.

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Noise robustness in coupled map lattice systems with applications

Behnam Kia, Sarvenaz Kia, John Lindner, Sudeshna Sinha and William Ditto

University of Hawaii at Manoa

A simple model for the noise effects in a coupled map lattice is presented. Using this model, we argue that the effects of local noise can be controlled and reduced by the dynamics of the coupled map lattice. Then we calculate the optimal value of coupling parameters between different nodes of the lattice to obtain the maximum amount of noise reduction. Multiple simulations are presented, and it is observed that there is agreement between the simulation results and the predictions of the theoretical model. We propose that coupled dynamics can operate as a noise filter, which has interesting engineering applications to conventional and chaotic computing. Then we compare the results of the presented method with the"majority wins" technique, where in order to obtain noise robustness, a series of similar systems operate at the same time and the result of the majority is selected as the final result. We observe that our coupling technique yields a higher level of noise robustness compared to the "majority win" technique.

This research is funded by the Office of Naval Research under award numbers N000141210026 and N00014-12-M-0378.

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Composition of attractor basins for dexterous robotic tasks

Daniel Koditschek

University of Pennsylvania

This talk reviews a two decade program of research in the design and implementation of modular controllers for dynamically dexterous robots. We seek to represent tasks by means of “templates:" low dimensional reference dynamics whose specified attractors encode goals and whose repelling boundaries represent obstacles or forbidden behaviors. General purpose machines typically have degrees of freedom unrelated to the needs of specific templates. Hence the most basic control module is an “anchor:" a feedback law that embeds the template as an attracting invariant submanifold in the machine’s physical state space. Synthesis of more complicated behaviors from simpler constituents proceeds by sequential and parallel composition of templates. A correct synthesis is one for which the limit set of the anchored composition yields the desired composition of the template limit sets. After reviewing various instances of these ideas applied to the setting of steady state legged locomotion, the talk concludes with a preliminary look at the problem of encoding and implementing transitional tasks such as leaping across gaps and onto ledges.

Quantum synchronization of quantum van der Pol oscillators with trapped ions

Tony Lee and Hossein Sadeghpour

ITAMP, Harvard-Smithsonian Center for Astrophysics

Van der Pol oscillators are prototypical self-sustained oscillators that have been used to study synchronization phenomena in classical systems. We study the van der Pol oscillator in the quantum limit, when the oscillator is near the quantum ground state, and the behavior is sensitive to the quantization of energy levels. We consider four scenarios: one oscillator with and without an external drive, two coupled oscillators, and an infinite number of oscillators with global coupling. We find that phase-locking is much more robust in the quantum model than in the equivalent classical model.

Quantum van der Pol oscillators also exhibit “entanglement tongues," which are the quantum analogue of Arnold tongues. In a classical system of two nonidentical oscillators, there is a critical coupling in order for the oscillators to phase-lock with each other. The critical coupling increases with detuning, giving rise to an Arnold tongue. In the quantum model, we find that there is a critical coupling strength in order for the oscillators to be entangled with each other, and the critical coupling increases with detuning.

Our results can be observed experimentally using trapped ions.

References

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Chaotic semiconductor lasers for ultrafast random bit generation

Nianqiang Li, Byungchil Kim, Vyacheslav Chizhevsky, Alexandre Locquet, Matthieu Bloch, David Citrin and Wei Pan

Georgia Institute of Technology

The nonlinear dynamics of semiconductor lasers have received considerable attention over the past few years. It is well accepted that semiconductor lasers are intrinsically stable when operating in a stand-alone, unperturbed condition; however, they can be easily destabilized by providing optical feedback by means of an external cavity. The resulting rich dynamics include intensity chaos, and this has been used for applications such as secure communication, reservoir computing, and random bit generation. Recently, there have been demonstrations of random-bit generation rates up to hundreds of Gb/s utilizing some offline post-processing algorithms.

In the present study, we employ a semiconductor laser with optical feedback to generate chaotic waveforms and explore its utilization for ultrafast random bit generation. We experimentally investigate two different approaches to random bit generation. We calculate the high-order finite differences of the generated chaotic waveforms in order to obtain highly symmetric statistical distributions of the chaotic laser intensity, which are well suited for random bit generation. In the first approach, an entropy measure provides an upper bound that is used as a practical limit to the extraction of several least significant bits from each sample. This guarantees that the allowed number of retained bits does not exceed the limit set by information theory. In the second approach, we aim for extracting more bits per sample using an effective post-processing technique that enables us to achieve much faster generation of physical-based pseudo random bits.

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Noise induced regime shifts in competitive population dynamics

Yen Ting Lin, Charles R Doering and Hyejin Kim

Max Planck Institute for the Physics of Complex Systems

Demographic stochasticity, the random fluctuations arising from the intrinsic discreteness of populations and the uncertainty of individual birth and death events, is an essential feature of population dynamics. Nevertheless theoretical investigations often neglect this naturally occurring noise due to the mathematical complexity of stochastic models. This talk reports the results of analytical and computational investigations of models of competitive population dynamics, specifically the competition between species in heterogeneous environments with different phenotypes of dispersal, fully accounting for demographic stochasticity. A novel asymptotic approximation is introduced and applied to derive remarkably simple analytical forms for key statistical quantities describing the populations' dynamical evolution. These formulas characterize the selection processes that determine which (if either) competitor has an evolutionary advantage. The theory is verified by conventional asymptotic analysis and large-scale numerical simulations.

We discover that the fluctuations can (1) support polymorphism that does not exists in deterministic models, (2) reverse the direction of the weak selection and cause shifts in selection regimes, and (3) allow for the emergence of evolutionarily stable dispersal rates. Both dynamical mechanisms and time scales of the fluctuation-induced phenomena are identified within the theoretical approach. The analysis highlights the fundamental physical effect of the fluctuations and provides an intuitive interpretation of the complex dynamics. An interaction between stochasticity and nonlinearity is the foundation of noise-driven dynamical selection.

References

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Controlling the position of traveling waves in reaction-diffusion systems

Jakob Löber and Harald Engel

TU Berlin

We present a method to control the position as a function of time of one-dimensional traveling wave solutions to reaction-diffusion systems according to a pre-specified protocol of movement. Given this protocol, the control function is found as the solution of a perturbatively derived integral equation. We derive an analytical expression for the space (x) and time (t) dependent control function $f(x,t)$ that is valid for arbitrary protocols and many reaction-diffusion systems. The control can be expressed in terms of the uncontrolled wave profile and its propagation velocity, rendering detailed knowledge of the reaction kinetics unnecessary. These results are close to controls computed numerically by an optimal control. An extension of the control method to two spatial dimensions allows to control the shape of traveling waves.

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Hydrodynamics affects self-organization and circulation in a bacterial drop

Enkeleida Lushi, Hugo Wioland and Raymond Goldstein

Brown University

Fluid dynamics plays an important role in transport, mixing, and many aspects of biophysical systems, yet its importance on self-organizing structures found in active and biological matter has not been fully understood. We investigate the influence of hydrodynamics on the emerging circulation and the orientational order of a dense bacterial suspension within small flattened droplets. In a recent experiment swimming B. Subtilis were shown to collectively form a steady single-vortex state with a counterrotating cell boundary layer. Using a minimal model and fast simulation method that captures oriented cell-cell and cell-fluid interactions, we show that hydrodynamics is crucial in reproducing and explaining the phenomenon observed in experiment. Simulations give insights into the microscopic arrangement and motion of the bacteria within the drops, and we confirm them with new experiments.

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Coherent structures in reacting flows

John Mahoney and Kevin Mitchell

UC Merced

Our goal is to characterize the nature of reacting flows by identifying important "coherent" structures. We follow the recent work by Haller, Beron-Vera, Blazevski and Farazmand [1, 2] which formalized the the notion of lagrangian coherent structures (LCSs) in fluid flows. In this theory, LCSs were derived from the Cauchy-Green strain tensor. We adapt this perspective to analogously define coherent structures in *reacting* flows. By this we mean a fluid flow with a reaction front propagating through it such that the propagation does not affect the underlying flow. A reaction front might be chemical (Belousov-Zhabotinsky, flame front, etc.) or some other type of front (electromagnetic, acoustic, etc.). While the recently developed theory of burning invariant manifolds (BIMs) describes barriers to front propagation in time-periodic flows, this current work provides an important complement by extending to the aperiodic setting. We use this formalism to describe the phenomenon of pinning in aperiodic flows.

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Fluctuation of similarity (FLUS) to detect transitions between distinct dynamical regimes in short time series

Nishant Malik, Norbert Marwan, Yong Zou, Peter Mucha and Juergen Kurths

University of North Carolina at Chapel Hill

Recently a method which employs computing of fluctuations in a measure of nonlinear similarity based on local recurrence properties in a univariate time series, was introduced to identify distinct dynamical regimes and transitions between them in a short time series [1]. Here we present the details of the analytical relationships between the newly introduced measure and the well known concepts of attractor dimensions and Lyapunov exponents [2]. We show that the new measure has linear dependence on the effective dimension of the attractor and it measures the variations in the sum of the Lyapunov spectrum. To illustrate the practical usefulness of the method, we employ it to identify various types of dynamical transitions in different nonlinear models. Also, we present testbed examples for the new method's robustness against the presence of noise and missing values in the time series. Furthermore, we use this method to analyze time series from the field of social dynamics, where we present an analysis of the US crime record's time series from the year 1975 to 1993. Using this method, we have found that dynamical complexity in robberies was influenced by the unemployment rate till late 1980's. We have also observed a dynamical transition in homicide and robbery rates in the late 1980's and early 1990's, leading to increase in the dynamical complexity of these rates. In another application we will apply this method to identify millennial-scale dynamical transitions in Plio-Pleistocene proxy records of the South Asian summer monsoon system. We infer that many of these transitions are induced by the external forcing of the solar insolation and are also affected by internal forcing on Monsoonal dynamics, i.e., the glaciation cycles of the Northern Hemisphere and the onset of the Walker circulation.

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Stabilizing by noise

Jonathan Mattingly

Duke University

The idea of noise stabilizing an otherwise deterministically unstable dynamical systems is often invoked in various modeling settings. Examples include PDEs such as the 3D Navier Stokes equation or Focusing NLS or ODEs modeling near wall flows or neural dynamics. In attempt to better rigorously understand the possible mechanisms in play, we will study the following class of model problems in the complex plane $\mathbf{C}$

$$\dot{z}(t) = z^{n+1} + c_n z^n + \cdots + c_1 z + c_0 + \dot{W}(t)$$

where $W(t) = \dot{\beta}(t) + i\dot{B}(t)$ is a standard complex-valued Brownian motion built from two standard real-valued Brownian motions and c_k are a collection of complex numbers.

When the noise is absence this system blows up in finite time for some initial conditions. Nonetheless, we will show that this system possesses a unique stationary density which simultaneously decays polynomially at infinity but attracts all initial distributions exponentially quickly. This might be surprising if one is used to thinking of reversible systems however this system possesses a circulation in equilibrium. We will be able to give a rigorous understanding of the polynomial decay rate of the invariant measure. Viewed as a time series this family of systems exhibits "intermittent" behavior in that it goes through long periods of relatively quiet behavior followed by dramatic spikes of high value. We will be able understand how the inter-spike times scale with the spike hight.

All ov these properties flow from a delicate balance between the blow up regions and the noise. Hence the structure of the instability feeds everything. We will give both a heuristic discussion of these facts and an induction of what tools are uses in the rigorous analysis. The discussion will touch on a number of topics including matched asymptotics, stochastic averaging, associated poisson equations, and Lyapunov functions.

This is joint work with David Herzog and builds on previous work of mine with Avanti Athreya and Tiffany Kolba and his with Jeremiah Birrell, Jan Wehr and Krzysztof Gawędzki.

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Breakup of invariant tori in volume-preserving maps

James Meiss

University of Colorado

Invariant tori are prominent features of Hamiltonian and symplectic dynamical systems that are integrable or nearly so. This arises in part because of the celebrated KAM theorem which shows the structural stability of certain “very irrational" (Diophantine) tori for “smooth enough" systems that are “anharmonic" (satisfy a twist condition). This robustness is responsible for the long time correlations and slow transport in chaotic Hamiltonian dynamics.Â

Each preserved torus is associated with a rotation (frequency ratio) vector that characterizes its dynamics. When the rotation vector is a scalar (two-tori for flows, one-tori for maps), the torus can be approximated in an optimal way by a sequence of periodic orbits obtained through the continue fraction expansion. This leads to Greene’s residue method, an extremely accurate technique for determining the breakup threshold of invariant circles in twist maps.

Generalization of these ideas to higher dimensional tori with rotation vectors has been difficult for a number of reasons. One is that there is no satisfactory generalization of the continued fraction. The second is that the instead of a single “residue", there are typically multiple quantities determining stability of Â periodic orbits.

We study three-dimensional, volume-preserving maps with invariant two-dimensional tori. Such tori act as transport barriers, and naive “crossing time" experiments can estimate their breakup threshold. We have generalized the residue criterion for the case that the maps are reversible. More generally, computations of the conjugacy to rigid rotation can be used to compute the threshold. The local singular values of these functions gives evidence for the existence of remnants after breakup, analogous to the cantori of symplectic maps.

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Stochastic pattern transitions in large scale delay-coupled swarms

Luis Mier y Teran, Brandon Lindley and Ira B Schwartz

Johns Hopkins University

Swarming patterns are ubiquitous in nature and an understanding of them is helping in the design of mobile sensor networks operating in uncertain environments. Here, we study the effects of time dependent noise and randomly distributed time delays on the dynamics of a large coupled system of self-propelling particles, or agents. Bifurcation analysis reveals that the system possesses bistable patterns with certain universal characteristics that depend on distinguished moments of the time delay distribution. Specifically, we show both theoretically and numerically that although bifurcations of simple patterns, such as translations, change stability only as a function of the first moment of the time delay distribution, more complex bifurcating patterns depend on all of the moments of the delay distribution. In addition, we show that there exists a noise threshold that forces a transition of the swarm from a disorganized misaligned state into a more organized aligned state. We show that this alignment transition exhibits hysterestic bistability when the noise intensity is taken to be time dependent. Finally, while the first order mean-field approximation is unable to capture pattern bistability, we show that a higher order mean-field approximation containing additional physics is able to do so.

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Coevolving voter models on networks

Peter Mucha, Feng Shi, Rick Durrett, Nishant Malik, James Gleeson, Alun Lloyd, David Sivakoff, Josh Socolar and Chris Varghese

UNC Chapel Hill

We consider idealized models of connected individuals changing their opinions and network connections in a coevolving process driving towards consensus. Discordant edges connecting disagreeing nodes are resolved either through one individual changing opinion to match the other or through a rewiring process, the details of which can lead to dramatically different results. We compare and contrast results for two opinions with two different rewiring systems: a "rewire-to-same" model where individuals form new connections only with others who already hold the same opinion, a "rewire-to-random" model where no constraints are made in the rewiring. We investigate this latter model in the presence of more than two opinions. Finally, we contrast these results with a more detailed model that reinforces local clustering with rewiring.

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Chemo-hydrodynamic patterning in reaction-diffusion advection systems

Alberto Muñuzuri

Univ of Santiago de Compostela

Speaker:

Reaction-diffusion systems have been extensively studied as they can explain many mechanisms of pattern formation in Nature ranging from biological waves to patterning in morphogenesis. Nevertheless, purely reaction-diffusion systems are rarely found in Nature but rather convection is always found to play an important role in all these processes. Here we present results that point out the important role played by convection in determining the pattern and dynamic to appear. A typical reaction diffusion system was used, the Belousov-Zhabotinsky reaction in experiments and the equivalent numerical model for simulations. The system spontaneously exhibited different types of patterns ranging from autowaves to Turing steady patterns depending on the parameters and particular type of reaction used. Different convective forcings were considered; a periodic modulation in the gravity that induces a specific, well-studied flow, a periodic modulation of a centrifugal force applied to the system, etc. The different results of these forcings on the different patterns and parameters ranges will be presented and understood in the framework of reaction-diffusion systems.

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Inferring phenomenological model of regulatory dynamics from data

Ilya Nemenman

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Models of cellular regulation often consist of large and intricate networks of interactions at the molecular scale, whose sheer size obfuscates understanding. Further, limited experimental data cannot easily constrain the many parameters of such detailed models, which then overfit and are not predictive. At the other extreme, simple ad hoc models of complex processes often throw the baby out with the bathwater. Here we propose a method that instead constructs phenomenological, coarse-grained dynamical models that adapt their level of detail to the amount of available data, leading to accurate predictions even when microscopic details are unknown, or when microscopically accurate models fail due to insufficient data. The computational resources required for the software realization of the method, named Sir Isaac, scale linearly instead of super-exponentially in the number of dynamical variables, allowing successful prediction even when important dynamic variables are unobserved. The inferred phenomenological models match the known phase space structure for simulated planetary motion data, avoid overfitting in a complex biological signaling system, and produce accurate predictions for a yeast glycolysis dynamical system model with only a handful of data points and many interacting species unobserved.

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Emergence of strange nonchaotic behavior by external noise

Keiji Okumura, Takahito Mitsui and Kazuyuki Aihara

The University of Tokyo

We study globally coupled quasiperiodically forced oscillators under the influence of noise. Using a nonlinear Fokker-Planck equation approach [1], the original Langevin equation is reduced to the deterministic equation of the order parameters of the system in the thermodynamic limit. The analytically obtained dynamical system of the order parameters exhibits strange nonchaotic dynamics [2] with increasing noise strength. This result suggests a novel picture of strange nonchaotic behavior with noise.

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Velocity-dependent coefficient of restitution measurements in an inelastic billiard experiment

Jeffrey Olafsen

Baylor University

As a class of non-equilibrium thermostatistical systems, driven granular media generate a large amount of dissipation in the particle-particle and particle-boundary interactions. Our understanding of the fundamental dynamics in these systems is complicated by the velocity-dependent nature of the coefficient of restitution of these interactions. A large number of very sophisticated experiments have sought to better understand and predict the velocity dependence of the coefficient of resitution by trying to constrain and control aspects of the particle-particle or particle-boundary collisions. Here, a careful and in-depth analysis from previously published results [1] for an inelastic billiard moving within a confining boundary allows the velocity-dependence to be measured as the dynamics freely evolve over multiple collisions in the driven system. The large amount of data generated in the experiment allows the contributions from both the normal and tangential velocity components in the particle-boundary interactions to be examined. A related experiment for particle-particle collisions will also be discussed.

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Mixing and piecewise isometries on a hemisphere

Paul Park, Paul B Umbanhowar, Julio M Ottino and Richard M Lueptow

Northwestern University

We study chaotic nonlinear dynamics and mixing on a hemispherical surface using piecewise isometries (PWI) motivated by cutting and shuffling in 3 dimensional (3D) granular flow. Under certain conditions, cutting and shuffling in a half-full spherical tumbler can be reduced to 2D PWI dynamics on a hemisphere. Simple rules for PWI transformations on a hemisphere can lead to complex behavior. Iterations of PWI for different parameters lead to a wide variety of patterns on the shell, which are referred to as the exceptional set (E). The taxonomy of E is broad, and can aid in understanding the observed variation in mixing with PWI parameters. Since PWI is volume preserving with bounded orbits, we employ Poincaré recurrence to obtain a coarse-grained measure for E using an isocube mapping which allows us to discretize the hemisphere with minimal distortion. Preliminary results suggest that E is a fat fractal whose characteristics promise to further our understanding of the complex dynamics and mixing that result from simple cutting and shuffling, i.e. PWI, and are applicable to 3D granular flows.

Symmetries, cluster synchronization, and isolated desynchronization in complex networks

Louis Pecora, Francesco Sorrentino, Aaron Hagerstrom, Thomas Murphy and Rajarshi Roy

Naval Research Laboratory

Many networks are observed to produce patterns of synchronized clusters, but it has been difficult to predict these clusters in general or understand the conditions for their formation. We show the intimate connection between network symmetry and cluster synchronization. We apply computational group theory to reveal the clusters and determine their stability. In complex networks the symmetries can number in the millions, billions, and more. The connection between symmetry and cluster synchronization is experimentally explored using an electro-optic network. We observe and explain a surprising and common phenomenon (isolated desynchronization) in which some clusters lose synchrony while leaving others connected to them synchronized. We show the isolated desynchronization is intimately related to the decomposition of the group of symmetries into subgroups. The results could guide the design of new power grid systems or lead to new understanding of the dynamical behavior of networks ranging from neural to social.

Analytic solution of the dynamics of quantum vortex reconnection

Itamar Procaccia

Weizmann Institute of Science

Experimental and simulational studies of the dynamics of vortex reconnections in quantum fluids showed that the distance d between the reconnecting vortices is close to a universal time dependence $d = [D[\kappa[t_0 - t]]^\alpha$ with α fluctuating around 1/2 and $\kappa = h/m$ is the quantum of circulation. Dimensional analysis, based on the assumption that the quantum of circulation $\kappa = h/m$ is the only relevant parameter in the problem, predicts $\alpha = 1/2$. The theoretical calculation of the dimensionless coefficient D in this formula remained an open problem. In this lecture I will present an analytic calculation of D in terms of the given geometry of the reconnecting vortices. We start from the numerically observed generic geometry on the way to vortex reconnection and demonstrate that the dynamics is well described by a self-similar analytic solution which provides the wanted information.

Tumor Models constrained by noninvasive imaging for cancer forecasting

Erin Rericha

Physics and Astronomy, Vanderbilt Univeristy

A major effort at the interface of cancer biology and the physical sciences is to develop validated mathematical descriptions of tumors that can be used to rationally design and evaluate clinical trials. The challenge is to build models that incorporate clinical data at the mesoscale, are consistent with local behavior at the cellular scale, and can be directly compared to the evolution of tumors in a patient. We present a candidate set of models that can be constrained by noninvasive imaging technologies and give preliminary comparisons between the model and clinical patient scans. We present early simulations of a simplified model designed to examine the robustness of the parameter extraction from noisy experimental data. Finally, we apply the formalism to the clinically relevant problem of detecting tumor resistance to targeted therapies.

Experimental signatures of chimera states in non-locally coupled boolean phase oscillators

David Rosin, Damien Rontani and Daniel J Gauthier

Duke University

Chimera states in dynamical networks have been found recently in several experiments using chemical, optical, and mechanical systems. However, most of these experiments still involve a computer to mediate the network coupling or rely on rather simple network topologies. Here, we overcome these limitations with novel Boolean realizations of coupled oscillators termed Boolean phase oscillators that are realized experimentally with embedded logic circuits. They include state-dependent delay, which allows weak phase adjustments when subject to coupling from neighboring nodes [1]. Using a field-programmable gate array (FPGA), we implement a ring of 100 non-locally coupled Boolean phase oscillators and measure experimentally frequency and phase in the network. We observe typical experimental signatures of chimera states, where parts of the network are synchronized and other parts are desynchronized.

We gratefully acknowledge the financial support of the U.S. Army Research Office Grant W911NF12-1-0099.

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Patterns in the wake of fronts

Arnd Scheel

University of Minnesota

We'll discuss pattern and wavenumber selection in the context of front propagation. We'll review linear selection criteria, state some nonlinear existence results, and then focus on front interaction. Applications include precipitation patterns, surface instabilities, and bacterial colony growth.

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Symmetry, controllability, and unification of dynamics in neuronal networks

Steven Schiff

Penn State University

The subtle and deep intersection of symmetry and controllability in brains and their physical models, offers critical open problems in both theory and experiment. I show recent examples of the use of nonlinear control theory for the assimilation and control of single neuron dynamics, as well as network motifs that have been well studied in epileptic seizures. We quantify observability and controllability in neuronal networks as a function of the connection topology and symmetry. We further have discovered an apparent unification between spikes, seizures, and spreading depression, which further opens a broad range of possibilities in the observation and control of neuronal dynamics.

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Calcium alternans as a phase transition in cardiac cells

Yohannes Shiferaw, Enric Alvarez Lacalle, Jon Spalding and Blas Echebarria

California State University, Northridge

Electrical alternans is a beat-to-beat alternation in the amplitude of the electrocardiogram (ECG) which has been shown to be a precursor to various cardiac arrhythmias. Many studies have traced this phenomenon to a disruption in subcellular processes such as calcium (Ca) cycling. However, the relationship between alternans and the properties of Ca signaling at the ion channel level is not completely understood. This is because Ca cycling is a spatiotemporal process that is due to the interaction of several thousand ion channels that regulate Ca cycling. In this talk I will present an overview of the basic architecture of Ca signaling in cardiac cells. I highlight the important role of stochastic signaling between ion channels and argue that nonlinearities inherent in the signaling architecture are essential to understand the onset of alternans. Furthermore, I will present evidence that the transition to alternans occurs via an order-disorder phase transition in the Ising universality class. Based on these results I will then argue that the onset of alternans in cardiac cells exhibits universal features common to a wide range of physical systems.

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Instabilities of a horizontal boundary separating two miscible liquids caused by vibrations

Valentina Shevtsova and Y Gaponenko, M Torregrosa, V Yasnou, A Mialdun

University of Brussels

The evolution of a horizontal interface separating two miscible liquids is examined numerically and experimentally under vibrations. The interface is represented as a transitional layer of small but nonzero thickness. The test liquids are the binary mixtures of water-isopropanol (IPA) of different concentrations. It well known that densities and viscosities of this mixture strongly depend on the concentration. The initial experimental configuration is hydrodynamically stable: the heavier liquid, 50%-50 % is placed at the bottom, and lighter one, 90% water -10% IPA, on the top. Translational periodic vibrations with a constant frequency and amplitude are imposed parallel to the interface between the two fluids.

The experiments were performed at the laboratory conditions and in microgravity, during the Parabolic flights, where the gravity level decreases by about 20 times [1]. The objectives of the microgravity experiments are to examine the ability of vibrations to enhance the flow, mixing, and interface distortions between two miscible fluids. Vibrational convection provides a mechanism of heat and mass transfer due to the existence of mean flows.

In the experiments under normal gravity we observed the frozen wave patterns along the interface. The waveform of this instability has triangular shape and limited height.

Totally different instability develops under microgravity conditions. The patterns had shape of tall columns perpendicular to the initial interface. The switching-off the vibrations leads to the instant mixing of the liquids. Our preliminary numerical results are in favourable agreement with the experimental results.

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Key bifurcations of bursting polyrhythms in 3-cell central pattern generators

Andrey Shilnikov, J Wojcik, R Clewley and J Schwabedal

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We identify and describe core bifurcations of networked bursting rhythms in 3-cell inhibitory/excitatory motifs of a multifunctional central pattern generator (CPG) —a neural microcircuit of interneurons whose synergetic interactions produce rhythmic activity with distinct phase-locked patterns that controls vital motor behaviors in animals. To study biologically plausible CPG models we develop a suit of computational tools that reduce the problem of stability and existence of rhythmic patterns in large networks to the bifurcation analysis of fixed points and invariant circles of PoincarÃ© return maps for phase lags between the burst initiation in the interneurons. Variations in coupling properties of the synapses between the CPG interneurons causing qualitative changes in the map's structure will result in the stability loss or the disappearance of the attractors of the map, along with the associated bursting patterns, through the core bifurcations. Our findings provide a systematic basis for understanding plausible biophysical mechanisms for the regulation of rhythmic patterns generated by various CPGs. The analysis does not require knowledge of the equations modeling the system, and provides a powerful qualitative approach to studying detailed models, which is applicable to a variety of biological phenomena beyond motor control.

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Synchronization in dissipative systems and Aubry-Mather theory

Siniša Slijepčević

University of Zagreb

We consider the driven Frenkel-Kontorova (FK) model

$$dx_n/dt = W'(x_{n+1} - x_n) - W'(x_n - x_{n-1}) - V'(x_n) + F, \tag{47.1}$$

where $(x_n)_{n\in\mathbb{Z}}$ is a configuration of a one-dimensional chain; W a convex interaction potential and V a 1-periodic potential. Furthermore, F is either a constant force (DC) or 1-periodic force (AC case). All results also hold for more general FK models, their continuous-time analogues (scalar reaction-diffusion equations), as well as second order equations with strong enough damping.

It has been known in the physics literature [1] that a solution of (47.1) is very often attracted to synchronized solutions regardless of the force and the initial condition. Here we give a rigorous explanation for that in terms of existence and uniqueness of physical invariant measures. We combine ergodic-theoretical tools with ideas from the Aubry-Mather and KAM theory of area-preserving twist maps, and from the theory of scalar reaction-diffusion equations (the lap number).

Recently independently Wen-Xin Qin [2] and the author in [4], following earlier results of Qin, Baesens, MacKay, and numerics ([1]), showed existence of totally ordered, minimal sets of (47.1) invariant for both spatial translations and time-evolution, for each rotation number $\rho \in \mathbb{R}$ nand in both AC and DC case; their union is denoted by $\mathcal{T}$. Such solutions are indeed synchronized, as trajectories of all particles are periodic or quasiperiodic and coincide up to space-time translation.

To understand their stability, we consider the union of supports (denoted by $\mathcal{A}$) of all space-time invariant measures of (47.1). Our key result from [4] (related results in [3]) is that $\mathcal{A}$ projects injectively to a 2d cylinder, and that the spatial shift is then pushed into a homeomorphism of a 2d cylinder. Thus the set $\mathcal{T}$ can be understood as a dynamical analogue of the union of Aubry-Mather sets of area-preserving twist maps. Furthermore, by Denjoy theorems, the set $\mathcal{T}_\rho$ of totally ordered orbits with an irrational rotation number ρ is isomorphic to either a circle or a Cantor set.

If $\mathcal{T}_\rho$ is a circle, in [5] we deduce from that the existence of a unique physical measure μ_ρ for the rotation number ρ. This means that, given any "reasonable" (i.e. of bounded width) initial condition with rotation number ρ, the space-time average of any observable (i.e. a continuous function on $\mathbb{R}^{\mathbb{Z}}$) converges to its expectation with respect to μ_ρ

We also use these tools to analytically explain numerically observed dynamical phase transitions of (47.1) by applying tools related to 2d twist maps, including KAM and converse KAM theory.

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Autonomous Boolean models of regulatory networks

Joshua Socolar, Mengyang Sun and Xianrui Cheng

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In cases where the dynamical properties of gene regulatory networks are important, a faithful model must include three key features: a network topology; a functional response of each element to its inputs; and timing information about the transmission of signals across network links. Autonomous Boolean network (ABN) models are efficient representations of these elements and are amenable to analysis. After discussing some generic features of ABN models, I will present an ABN model of the gene regulatory network governing cell fate specification in the early sea urchin embryo – a pattern formation problem in which three bands of distinct tissue types must be generated through a combination of network dynamics and cell divisions, beginning from an initial condition with only two distinct cell types. I will also present a classification of stable oscillatory attractors in a figure-8 network and compare the ABN behavior to ODE dynamics. [Supported by NSF Grant DMS-10-68602.]

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Experimental basins of attraction

Lawrie Virgin, Richard Wiebe and Joshua Waite

Duke University

A key feature of many nonlinear dynamical systems is the presence of co-existing solutions, i.e, nonlinear systems are often sensitive to initial conditions. While there have been many studies to explore this behavior from a numerical perspective, in which case it is trivial to prescribe initial conditions (for example using a regular grid), this is more challenging from an experimental perspective. This presentation will discuss the basins of attraction extracted from a simple mechanical experiment. By applying stochastic perturbations to steady-state behavior, it is possible to interrogate the initial condition space and map-out basins of attraction as system parameters are changed. This provides a more complete picture of possible behavior than conventional bifurcation diagrams with their focus on local steady-state behavior.

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The dynamics of phage-bacteria communities: from ecology to evolution (and back again)

Joshua Weitz

Georgia Institute of Technology

Phage (i.e., viruses that exclusively infect bacteria) are ubiquitous in the environment. For example, reports of 10-100 million phage per ml of seawater are common, a density approximately ten-fold higher than that of their bacterial hosts. Phage can function like bacterial predators, regulating the amount and diversity of bacterial hosts present in a community. However, efforts to understand the dynamics of complex phage-bacteria communities are still in their infancy. Here, I review formative studies of the nonlinear population dynamics of phage-bacteria communities, focusing on simplified model systems in the laboratory (developed by Bruce Levin and colleagues [1]) and in marine surface waters (developed by Frede Thingstad and colleagues [2]). These studies provide a setting-off point for recent work in which we consider (i) how changes in the relative frequency of bacterial and viral strains can lead to novel forms of ecological dynamics [3]; and (ii) mechanisms through which many strains of phage and bacteria can coexist [4], despite being characterized by complex and overlapping networks of infection [5].

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Part II

Poster Session A - 3:40PM to 5:10PM Friday, January 3

P.1

Non-universal anomalous diffusion and adsorption in asymmetric random walks on hierarchical networks

Lauren Ball, Afred Farris and Stefan Boettcher

Emory University

We study an asymmetric random walk on a network consisting of a one-dimensional line and hierarchy of small-world links, called the Hanoi network [1]. Walkers are biased along the one-dimensional line, and move in the opposite direction only along the long-range links with a probability p. We study the mean-square displacement $\langle r^2 \rangle \sim t^{\frac{2}{d_w}}$ and find that the anomalous diffusion exponent d_w depends on p. The behavior ranges from ballistic motion ($d_w(p = 0) = 1$) to an adsorped state ($d_w(p_c) = \infty$). This phase transition to the adsorped state occurs at a finite $p_c < 1$. We use simulations and the renormalization group to determine these properties.

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P.2

A comparative study on the co-existing attractors in the hierarchy of q-deformed nonlinear maps with an invariant measure

Sohrab Behnia and Mohamad Yahyavi

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Quantum groups theory have contributed greatly of mathematicians and physicists towards the particular mathematics branch dealing with versions of q-numbers (Heine 1846), q-series, q-functions, q-exponentials (Jackson 1904), q-differentials etc., with a history going back to the early part of the 19th century [1–3]. In general, there are no unique q-deformation for a function, however, one of the simplest definitions of a q-deformation is includes the modification of a function so that under the limit of $q \to 1$ the usual function is obtained. Therefore there are available various q-deformations of the same function in different physical and mathematical contexts. Significant strides have been made for studding of different types of q-deformations for logistic map, which is one of the famous model of discrete nonlinear dynamical systems. The authors of Ref. [**?**] showed that the co-existence of attractors in q-logistic maps. Patidar *et al.* [**?**] compared that the dynamical behaviour of the q-deformed Gaussian map and Gaussian map. Recently, Shrimali *et al.* [**?**] demonstrated that the effect of delay on two forms of q-deformations of the logistic map. Also, they argued that chaotic behaviour is suppressed in a certain region of delay and deformation parameter space. Almost every initial condition in the corresponding basin of the attractor. Recently, the authors of Ref [**?**, **?**] have studied the hierarchy of chaotic maps with an invariant measure. The map (Jef map) was first suggested in 2001 by their group and is defined by use of the Chebyshev polynomial which induces the hierarchy. An important feature of the map is that there exists a transition parameter α_c: the fixed point is stable for $\alpha < \alpha_c$, the point is neutral for just $\alpha = \alpha_c$ and intermittency occurs, and trajectories are chaotic for $\alpha > \alpha_c$ and the SRB measure is absolutely continuous with respect to the Lebesgue measure. These maps can be defined as:

$$\Phi(x,\alpha) = \frac{\alpha^2 F}{1 + (\alpha^2 - 1)F} \ . \tag{P.2.1}$$

Where F substitutes with Chebyshev polynomial of type one, $T_N(x)$ for $\Phi_N^{(1)}(x,\alpha)$ and in the case of Chebyshev polynomial of type two, $U_N(x)$ for $\Phi_N^{(2)}(x,\alpha)$. The conjugate maps of the one parameter families of chaotic maps which are used in derivation of their invariant measure and calculation of their generalized Lyapunov exponent are defined as:

$$\tilde{\Phi}_N^{(1)}(x,\alpha) = h \circ \Phi_N^{(1)}(x,\alpha) \circ h^{-1} = \frac{1}{\alpha^2} \tan^2(N \arctan \sqrt{x}), \tag{P.2.2}$$

$$\tilde{\Phi}_N^{(2)}(x,\alpha) = h \circ \Phi_N^{(2)}(x,\alpha) \circ h^{-1} = \frac{1}{\alpha^2} \cot^2(N \arctan \frac{1}{\sqrt{x}}). \tag{P.2.3}$$

Conjugacy means that the invertible map $h(x) = \frac{1-x}{x}$, maps $I = [0,1]$ into $[0,\infty)$. As an example, some of these maps are given below:

$$\Phi_2^{(1)} = \frac{\alpha^2(2x-1)^2}{4x(1-x) + \alpha^2(2x-1)^2}, \qquad \Phi_2^{(2)} = \frac{4\alpha^2 x(1-x)}{1 + 4(\alpha^2-1)x(1-x)},$$
$$\Phi_3^{(1)} = \Phi_3^{(2)} = \frac{\alpha^2 x(4x-3)^2}{\alpha^2 x(4x-3)^2 + (1-x)(4x-1)^2}. \tag{P.2.4}$$

We have derived analytically their invariant measure for arbitrary values of the parameter α and every integer values of N

$$\mu_{\Phi_N^{(1,2)}(x,\alpha)}(x,\beta) = \frac{1}{\pi}\frac{\sqrt{\beta}}{\sqrt{x(1-x)}(\beta+(1-\beta)x)} \ . \tag{P.2.5}$$

with $\beta > 0$ is the invariant measure of the maps $\Phi_N^{(1,2)}(x,\alpha)$ provided that, we choose the parameter α in the following form:

$$\alpha = \begin{cases} \frac{\Sigma_{k=0}^{[\frac{(N-1)}{2}]} C_{2k+1}^N \beta^{-k}}{\Sigma_{k=0}^{[\frac{N}{2}]} C_{2k}^N \beta^{-k}} & \text{for} \quad \text{odd values of } N \\ \\ \frac{\beta \Sigma_{k=0}^{[\frac{(N)}{2}]} C_{2k}^N \beta^{-k}}{\Sigma_{k=0}^{[\frac{(N-1)}{2}]} C_{2k+1}^N \beta^{-k}} & \text{for} \quad \text{even values of } N \end{cases} \tag{P.2.6}$$

where the symbol [ ] means greatest integer part. Using the above hierarchy of families of one-parameter chaotic maps we can generate new hierarchy of q-deformed nonlinear maps Eq.(refqd), based on the non-extensive statistics of Tsallis with an invariant measure. Now, the hierarchy of the q-deformed nonlinear maps can be defined as:

$$\begin{cases} \Psi_N(x_{n+1},\alpha) = \Phi_N([x_n],\alpha) \\ \\ [x] = \frac{x}{1+(1-q)(1-x)} \end{cases} \tag{P.2.7}$$

Here $-\infty < q < -2$ for x in the interval $[0,1]$ and x_n denotes the value of x after n iterations. Also, when $q \to 1$ hierarchy of q-deformed nonlinear maps becomes the usual maps. As examples by considering the $\Phi_N^1(x,\alpha)$ families, we have generate the following examples:

$$\Psi_2(x_{n+1},\alpha) = \frac{4\alpha^2(1+\varepsilon)x(1-x)}{(1+\varepsilon)^2 + x\left(4(\alpha^2-1) - 2\varepsilon^2 - 2\varepsilon\right) + x^2\left(4(-\alpha^2+1)+\varepsilon^2\right)} \tag{P.2.8}$$

$$\Psi_3(x_{n+1},\alpha) = \frac{\alpha^2 x\left(x(3\varepsilon+4) - 3(1+\varepsilon)\right)^2}{\alpha^2 x\left(x(3\varepsilon+4) - 3(1+\varepsilon)\right)^2 + \left((1+\varepsilon)(1-x)\right)\left(x(\varepsilon+4) - (\varepsilon+1)\right)^2} \tag{P.2.9}$$

Therefore, the progresses of this study are the derivation of the generalized Lyapunov exponents by an additional parameter (q). Numerical analysis for co-existence of attractors property and singularity of the invariant density is done for changing the q-parameter. In this communication, inspired by the non-extensive statistics of Tsallis [**?**, **?**], we discuss the effect of ergodicity (Birkhoff ergodic theorem) on two forms of q-deformations of the hierarchy of exactly solvable one-parameter family of 1D chaotic maps. Moreover, we discuss a relationship between the generalized Lyapunov exponent and the sensitivity to initial conditions. The general concept proposed in this paper appears quite robust. As a result, we have found that the map exhibit a wide variety of dynamical behaviors including the co-existence of attractors (that is uncommon phenomenon in 1D maps).

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P.3

Dynamics of asynchronous networks

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The dynamics of networks govern our everyday lives. These include networks on many scales, from multiple interacting computer cores to logistic networks which span our entire planet. Even human interaction may be interpreted as a network of human nodes where links are constantly established and deleted. From a phenomenological point of view, the interaction of two nodes may only interact for a specific amount of time and different nodes in the network may also evolve independent of one another. Parallel computing is one of the prime examples; interaction between threads takes place only when they synchronize and a thread may stop until the next synchronization event. Traditionally, smooth systems of ordinary differential equations have been used to describe the dynamics of many networks. Due to the regularity constraints on the solutions, these "synchronous" networks fail to incorporate for example stopping phenomena. Hybrid dynamical systems can capture some of the phenomenological phenomena but they have mostly been studied in an engineering context.

We describe the dynamics of "asynchronous" networks which aims at capturing the dynamics of networks including for example stopping, disconnecting, and reconnection events. Networks consist of interacting nodes and the term asynchronous here refers to the possibility that each node runs on its own clock, independent of other nodes. We introduce the concept of an asynchronous network through multiple examples and give a first formal definition. Moreover, we discuss similarities and differences between the dynamics of asynchronous networks and more classical approaches such as hybrid and piecewise smooth dynamical systems.

P.4

Acoustic detection and ranging using solvable chaos

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US Army AMRDEC

Acoustic experiments demonstrate a novel approach to ranging and detection that exploits the properties of a solvable chaotic oscillator. This nonlinear oscillator includes an ordinary differential equation and a discrete switching condition. The chaotic waveform generated by this hybrid system is used as the transmitted waveform. The oscillator admits an exact analytic solution that can be written as the linear convolution of binary symbols and a single basis function. This linear representation enables coherent reception using a simple analog matched filter and without need for digital sampling or signal processing. An audio frequency implementation of the transmitter and receiver is described. Successful acoustic ranging measurements in the presence of noise and interference from a second chaotic emitter are presented to demonstrate the viability of the approach [1].

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P.5

Quantum walks and interference without translational invariance

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We provide a general method to solve the evolution equations for a quantum walk on fractals based on renormalization. We introduce the method by efficiently reproducing well-known results on the one-dimensional lattice. Applied to the dual Sierpinski gasket, our treatment of the quantum walk reveals an immensely rich phenomenology for the dynamics of spreading in a system characterized by hierarchically structured loops, bottlenecks, and generally: lack of translational invariance. Invariably, quantum interference localizes the walk completely with an access probability that declines with a powerlaw from the initial site, where a classical random walk would pass all sites with certainty. Nonetheless, we find that under rescaling the system length, $L' = 2L$, time rescales as $t' = 2^{d_w} t$ with the "diffusion" exponent $d_w = \log_2 \sqrt{5} = 1.1609\ldots$, very close to the ballistic spreading, $d_w = 1$, found for regular lattices.

P.6

Demon design: circumnavigating Landauer’s limit

Alec Boyd and James Crutchfield

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Maxwell’s Demon is a century old thought experiment which has challenged physicists’ understanding of thermodynamics. We develop a new classical formalism for constructing generalized Maxwell’s Demons. We call this new class of systems information engines. These engines use "intelligent" information processing to extract energy from a thermal bath. Although these processes appear to violate the second law of thermodynamics on first inspection, information processing has an energy cost. This cost was once thought to be described by Landauer’s limit on erasure. We discuss how to design the microscopic and macroscopic architecture of the information engine in order to circumnavigate Landauer’s Principle, developing a different set of energetic bounds on information processing.

P.7

Point-wise finite time Lyapunov exponent, optimal sampling strategy and probabilistic source regions

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In an autonomous system the invariant manifolds control the overall configuration of the phase space. Similarly, the hyperbolic Lagrangian coherent structures (LCSs) which are associated to the finite time Lyapunov exponent (FTLE) fields are the pathways that control the global configuration of the flow maps in the extended time varying phase spaces. These features are also the co-dimension 1 manifolds and boundaries of the coherent structures since they are locally the strongest repelling or attracting material surfaces. Classical interpretation of FTLE-LCSs provides a powerful framework for understanding transport and mixing phenomena especially in the case of passive particles in fluid systems. Increasing number of geophysical fluid studies use concepts of FTLE-LCSs to describe and/or predict time evolution of Lagrangian systems such as oil spill or volcanic ash distribution. In some applications we have sparse information about the system, while there is a huge interest for knowing about the past or future of mesoscale Lagrangian configurations. For example, in aerobiological studies there are usually very few localized (sometimes consecutive) measurements of microbial structure of atmosphere. Meanwhile, finding the earlier or upcoming distribution of pathogens is important for many practical means. Regarding this issue, we propose a new perception of FTLE-LCSs which is useful when we have localized information. This description helps us to have a better understanding about deterministic distribution of source points of sampled particles. We also investigate the uncertainty of the deterministic solutions by considering unresolved turbulence. Our results show the relation between passing LCS features over a fixed geographical location and the optimal time for collecting atmospheric samples when capturing the most diverse type particles (e.g., spores, microorganisms) is desirable. Also we demonstrate that even in cases that unresolved turbulence has significant effects, the proposed sampling strategy works well and the collected samples would be from sufficiently diverse origins.

P.8

Topological analysis of chaotic transport through a ballistic atom pump

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We examine a system consisting of two reservoirs of particles connected by a channel. In the channel are two oscillating repulsive potential-energy barriers. It is known that such a system can transport particles from one reservoir to the other, even when the chemical potentials in the reservoirs are equal. We use computations and the theory of chaotic transport to study this system. Chaotic transport is described by passage around or through a heteroclinic tangle. Topological properties of the tangle are described using a generalization of Homotopic Lobe Dynamics (HLD), which is a theory that gives some properties of intermediate-time behavior from properties of short-time behavior. We compare these predicted properties with direct computation of trajectories.

P.9

Vortex dynamics in cerebral aneurysms

Greg Byrne

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We use an autonomous three-dimensional dynamical system to study embedded vortex structures that are observed to form in computational fluid dynamic simulations of patient-specific cerebral aneurysm geometries. These structures, described by a vortex which is enclosed within a larger vortex flowing in the opposite direction, are created and destroyed in phase space as fixed points undergo saddle-node bifurcations along vortex core lines. We illustrate how saddle-node bifurcations along vortex core lines also govern the formation and evolution of embedded vortices in cerebral aneurysms under variable inflow rates during the cardiac cycle.

P.10

Understanding information creation, destruction, and storage in a chaotic system

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One of the distinctive features of a deterministic chaos is that it creates information. The rate of the information creation is given by the Kolmogorov-Sinai metric entropy. Ever since its introduction, metric entropy has been used to measure unpredictability of a chaotic system. However, this view does not tell a full story about the created information. A portion of the created information is forgotten by the system (ephemeral information), while another portion is remembered (bound information). Using symbolic dynamics, we calculate these information measures and show that they tell a much richer story than metric entropy alone. Finally, we connect the bound and ephemeral information to the underlying behavior of a chaotic system.

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P.11

A bifurcation controlling temporal characteristics in a bursting neuron

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An open question in Neuroscience is how the temporal characteristics of bursting activity and transient neuronal responses are controlled by intrinsic biophysical characteristics. These dynamical cellular mechanisms determine excitability and oscillatory neuronal activity. We present a family of mechanisms organized around a global codimension-2 bifurcation. This bifurcation follows one of the generic scenarios described for the blue sky catastrophe [1]. This cornerstone bifurcation satisfies the criteria for both the blue sky catastrophe and the saddle-node bifurcation on an invariant circle (SNIC). The burst duration and interburst interval increase as the inverse of the square root of the difference between the corresponding bifurcation parameter and its bifurcation value. The cornerstone bifurcation also determines the stereotypical transient responses of silent and spiking neurons. In this report, we demonstrate the cornerstone bifurcation in a three dimensional Hodgkin-Huxley style neuronal model. This research was supported by NSF grant PHY-0750456.

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P.12

Bouncing bifurcations: A comparison of the bifurcation and chaotic behaviors between two dynamical systems

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A bouncing ball on a sinusoidally vibrating plate is a classic physics model that has been thoroughly studied over the last few decades with the results being utilized for various applications. Similarly, a droplet bouncing on a bath of the same viscous fluid that oscillates vertically has been a popular subject of study in recent years to gain further insight into applications of fluid dynamics. In this presentation, we analyze the bouncing ball model and compare our findings with results obtained from our laboratory experiments with bouncing droplets of silicon oil to investigate whether the two systems exhibit similar bifurcation and chaotic behavior. For the bouncing ball model, we identify the equations of motion and a coefficient of restitution and construct a system of iterated equations with dimensionless parameters while employing the high-bounce approximation to simplify the analysis of the behavior of the bouncing ball. We then determine the fixed points of the system and mathematically analyze where the threshold of bifurcation occurs and when chaotic regimes materialize. With the use of computer software, we vary the values of the dimensionless parameters of the iterated equations to plot the dynamics of the bouncing ball model and create bifurcation diagrams to aid our analysis. In our laboratory experiments, a shallow bath of silicon oil of a particular viscosity was placed on an electromagnetic shaker where it was driven by a constant frequency just below the threshold of Faraday instability. A small droplet of the same viscosity was then manually created on the surface of the vibrating bath such that the droplet was sufficient in size so as not to coalesce with the silicon bath. The bouncing behavior of the droplet was observed and recorded with the aid of a high-speed camera. Computer software was utilized to process the images and plot the dynamics of the droplet.

P.13

Nonlinear cross field coupling and the route to broadband turbulence in a linear magnetized helicon plasma device

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In the linear magnetized helicon plasma device CSDX (Controlled Shear De-correlation eXperiment), drift interchange modes are typically found to coexist on top of a weak-turbulence driven azimuthally symmetric, radially sheared plasma. With increasing magnetic field strength, the system can be driven to fully developed broadband turbulence. Fast framing camera imaging is used to study the dynamics in the azimuthal-radial cross section. Nonlinear cross-field coupling between drift eigenmodes at different radial positions is investigated using azimuthal Fourier decomposition. The coupling strength between waves at different radial positions is inferred from radial profiles and cross-field transport between adjacent magnetic flux surfaces. Nonlinear effects like synchronization, phase slippages, phase pulling and periodic pulling are observed. The effects of mode coupling and the stability of modes are compared to the dynamics of a coupled chain of Kuramoto oscillators. Both theoretical results from the Kuramoto model and experimental results from the CSDX device shall be presented.

P.14

Chaotic dynamics of a bouncing drop on a vibrating fluid bath

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Droplets bouncing on a vertically vibrated fluid bath can exhibit complex dynamics, including chaotic motion, the assembly of multiple drops into lattice structures, and self-propelled 'walkers' that mimic quantum behavior. In order to fully understand the underlying mechanisms that give rise to these diverse phenomena, an effort has been made to study this system in various limiting cases. A recent series of papers has investigated the vertical motion of low-viscosity, bouncing drops over a range of driving frequencies, amplitudes and drop diameters. In this paper, we extend these efforts to explore the dynamics of moderately viscous (100-200 cSt) drops bouncing on a vertically vibrating bath of the same fluid. High-resolution imagery is used to track drop deformation and center-of-mass motion during impact. Periodic and chaotic bouncing modes are identified from the pattern of drop acceleration peaks and points of contact with the fluid bath. We measure bifurcation sequences as the acceleration amplitude and drop diameter are varied. We compare our experimental results using viscous drops to previously published linear models and suggest that their ability to reproduce our observed bifurcation sequences may be improved by the addition of a nonlinear damping term.

P.15

Saline oscillators as a characterization of cardiac dynamics

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Studying cardiac dynamics and nonlinear systems, our group would like to present a poster about saline oscillators. Saline oscillators provide a simple, inexpensive system to study nonlinearity. These oscillators give a periodic signal resembling the action potential of the heart. Our group aims to provide an equation relating the period of oscillation with four different parameters. So far, we realized that one of the parameters seems to not affect the period. In addition, in a certain range, the salinity affects the period in an unpredictable manner. Furthermore, we would also like to observe more similarities between the saline oscillator and the heart by perturbing the oscillators to bring about alternans, Wenckebach rhythms, and chaos signals.

P.16

New geometric methods to study high-dimensional transients in the nonlinear dynamics of biological networks

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Transient dynamics are abundant in biology: they describe how stable systems respond to perturbations and they are a predominant feature of behaviors as diverse as limb manipulation and membrane excitability, whose mechanisms can be composed of many transiently interacting elements. Unfortunately for our modeling of such systems, transients in the solutions of high dimensional systems of ODEs can be difficult to analyze with traditional linearization techniques [1].

We adopt a pragmatic computational approach that is well suited to biological applications where the goal is qualitative insight rather than analytic precision. Our approach is effective in highly dissipative biological systems whose components are connected in relatively sparse configurations. In such cases, we can analyze partition any trajectory into 'epochs' according to changes in the pattern of dominant sensitivity quantities [2]. An algorithmic, piecewise reduction according to these principles closely mimics the results of applying a formal asymptotic analysis of the dynamics [3,4], and can be seen as an automated approximation of such an analysis away from formal limits of time scale separation.

A new aspect of our approach is to analyze 2D projections of high-dimensional local epochs using a careful modification of traditional phase plane techniques. These modifications allow us to track the quality of our approximate analysis of an epoch with 2D pictures. It also allows us to build a mechanistic causal description that interprets the transient dynamics using conserved geometric features in a way that is useful to experimental biologists and to model inference and optimization. A clearer understanding of transient biophysical mechanisms will better connect microscopic and macroscopic processes relevant to dynamic, multi-scale diseases. In particular, knowledge of mechanisms can better guide us to new, and more subtle, forms of genetic or drug therapy.

We present overviews of two recent applications of our approach. The first result is a detailed biophysical explanation of the phase response curve (PRC) of a repetitively spiking cell membrane [5,6]. This explanation is important because the PRC is a commonly used predictive tool whose practical definition relies on empirical measurement, but which has limited utility without a mechanistic justification. Our second application is to a 43-dimensional model of a cardiac cell [7]. Ion channel mutations cause pathological action potentials that underlie arrhythmias. Our technique goes beyond existing methods that directly compare the interplay of currents to uncover indirect relationships between them.

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P.17

Propagating precipitation waves: experiments and modeling

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Traveling waves are a widespread dynamical phenomenon observed in both living and nonliving systems. Examples include calcium waves propagating through Xenopus laevis oocytes, cyclic AMP waves in colonies of Dictyostelium discoidem cells and spiral waves in propagating flames fronts. Recently, research on a precipitation reaction involving AlCl3 and NaOH has provided another example of traveling waves. In this system, the Al3+ ions are immobilized within a gel matrix into which OH- ions diffuse, causing solid Al(OH)3 to form. Owing to the amphoteric nature of the precipitate, continued diffusion of the hydroxide results in the redissolution of the precipitate with the formation of Al(OH)4- . It is generally accepted that the mechanism for traveling waves requires the coupling of a positive feedback process, such as autocatalysis for chemical systems, with transport. However, the AlCl3-NaOH reaction does not involve chemical autocatalysis. A novel model based on a sol-coagulation model of Liesegang bands with redissolution was developed for this system. The wave dynamics is characterized by the growth and redissolution of a diagonal precipitation feature that migrates through a colloidal precipitate band.

P.18

Reduction of continuous SO(2) symmetry of a 2-mode system using method of slices

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Danglmayr [1] and Porter & Knobloch [2] have introduced a family of 2-Fourier mode SO(2)-equivariant ODEs in order to study bifurcations of solutions of dynamical systems in presence of symmetries. A 4-dimensional system of this kind is perhaps the simplest example of a system with a continuous symmetry that can exhibit chaos, so we use it to illustrate the role symmetries play in chaotic dynamics. We show that a continuous symmetry induces drifts in the 4-dimensional state space dynamics, drifts which obscure the chaotic dynamics. Change of equations of motions to a locally symmetry-invariant 'comoving' frame does not eliminate these drifts: that is only attained by a *symmetry reduction* - reformulation of dynamics in a 3-dimensional symmetry-reduced state space, where every group orbit (set of all points reached by actions of the group of all symmetries of the equations of motion) is replaced by a point. Porter & Knobloch system is a particularly nice illustration of how this works, as in 3 dimensions we are able to visualize everything.

We compare three symmetry reduction methods: polar coordinates, invariant polynomial bases, and the 'method of slices'. An invariant polynomial basis is convenient for determination of all relative equilibria of such system. Our conclusion, however, is that the most insight is offered by the method of slices. While in general a number of local slices are needed to cover a strange attractor [3], for the Porter & Knobloch system there we define a unique slice hyperplane that captures *all* symmetry-reduced dynamics. A Poincaré return map within the slice hyperplane enables us to reduce the dynamics further, essentially to a unimodal map, and determine, in principle, all relative periodic orbits of the system. We can visualize each step of this process without having to project solutions onto a submanifold since the slice hyperplane for this system is three dimensional. We argue that our method can reduce the SO(2)-symmetry also for N-Fourier modes truncations of PDEs such as the Kuramoto-Sivashinsky, pipe flows, etc., as long as the amplitude of the first Fourier mode is non-zero.

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P.19

Constructive methods for quai-periodic solutions

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We will present some methods to prove KAM theorems which are well suited for numerical computations.

The methods lead to very efficient algorithms and can also validate the computed results (they have an a-posteriori format, which shows that any approximate solution that has some moderate condition numbers leads to a true solution).

We will present two geometric contexts: Conformally symplectic systems (an example is systems with friction proportional to velocity) and volume preserving systems.

P.20

Biomimetics and synthetic biology: A dynamical perspective

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For many years, technological improvements and scientific research have been inspired by biological systems: from Leonardo's flying machines, Velcro^{TM} to modern robots which mimic some functions in model organisms, we can adapt basic design principles from Nature.

On the biological side, many new technologies related with the modification of the genetic code have been developed. On the other hand, sophisticated manipulation of physical systems at the nano scale is nowadays common. Unfortunately nanotechnology is usually complex and expensive.

Biomimetics allows for the convergence of these two approaches. It is therefore very important to understand from a dynamical perspective the complexity exhibited by living systems in order to create and improve technology.

In this work we present several examples from synthetic biology related to this interaction. Among them, we discuss the synthesis of an antifreezing protein,the construction of a cold sensor, an activator-inhibitor genetic circuit related to the study of Turing patterns, and a circuit which produces light from *Vibrio phosphoreum* via *quorum sensing*. In particular, we present a mathematical model based on a continuum approach that leads to a nonlinear wave equation and argue that travelling waves represent luminiscence synchronization fronts

$$u_{tt} - u_{xx} + f(u) = 0,$$

where f is a function reminiscent of the van der Pol nonlinearity.

We also discuss some issues related to instrumentation and how nanotechnology and open source microcontrol techniques can be used in biosynthetic constructions.

P.21

Numerical results for linearization of fibered holomorphic maps

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We study quasi-periodically perturbed complex mappings with a fixed point on $\mathbb{C} \times \mathbb{T}^1$:

$$f_\delta(z, \theta) = (az + z^2(1 + \delta\cos(\theta)), \theta + \omega)\,,$$

where $a = e^{2\pi i \nu}$, and ν, ω satisfy a diophantine condition.

It has been shown [1,2] that there exists a domain in which f is conjugated to a rotation $R_{\nu,\omega}(z, \theta) = (az, \theta + \omega)$.

We study numerically the behaviour of the conjugacy function as it approaches the boundary, and we discover that there are some novel scaling relations.

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P.22

Lyapunov exponents, Floquet exponents and covariant vectors of Kuramoto-Sivashinsky equation

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Georgia Institute of Technology

The largest positive Lyapunov exponent has long been used as an indicator of chaotic dynamics, and recently sets of 'covariant Lyapunov vectors' have been shown to determine the 'physical dimension' of a strange attractor [1] of a spatially extended flow, for ex. the Kuramoto-Sivashinsky on a finite periodic domain. Such system can have a large range of Lyapunov exponents, some expanding rapidly along the few unstable eigen-directions, while others contract dramatically along the many stable eigen-directions. It is a challenge to calculate those exponents accurately; the *QR iteration* [2] provides a practical way to evaluate them.

The evolution of the tangent space of a dynamic system is governed by the Jacobian matrix $\delta x(x_0, t) = J^t(x_0)\, \delta x(x_0, 0)$. For a periodic orbit, the eigenvalues of the Jacobian matrix are called the Floquet multipliers, and the associated Floquet eigenvectors define the invariant directions of the tangent space. The eigen-equation cannot be solved in the traditional way, as the magnitude of matrix elements in such Jacobian matrix can easily range over 100 orders of magnitude. We show that the *periodic Schur decomposition* [3] enables us to compute *all* eigenvalues to a high precision, provided the dimension (the number of spatial Fourier modes) is not too high.

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P.23

Inferential evolution, complexity, and the reflection principle

Christopher Ellison, Jessica Flack and David Krakauer

University of Wisconsin

An intriguing and fundamentally unsolved problem in our understanding of life on Earth is to explain the existence of complex life. The difficulty stems, in part, from having no explicit relationship between evolutionary dynamics and complexity theory. In this work, we consider the environment and how it influences organismal complexity. To do so, we recast evolution as a Bayesian inferential framework in which organisms update hidden Markov model priors of the environment into posteriors by incorporating information from Bayesian networks of the environment and other organisms. Information-theoretic measures of complexity are then used to directly compare organismal complexities to the environment's complexity and also to each other. As organisms evolve, they learn about the environment and its regularities, and so, complex life can be seen as an evolutionary consequence of organisms learning in complex environments.

P.24

Engines on the edge: Long memory and mode switching in internal combustion engines

Charles E A Finney, Brian C Kaul, Derek A Splitter, C Stuart Daw and Robert M Wagner

Oak Ridge National Laboratory

Spark-ignited internal combustion engines have evolved considerably over the past few decades to meet increasingly stringent emissions and fuel-economy regulations. These changes have involved overcoming major technical challenges in engine design, materials and control. Two specific modifications that have been favored in advanced engine designs are high levels of exhaust gas recirculation (EGR) and homogeneous charge compression ignition (HCCI). In the former, ignition is initiated using an electric spark, but the added exhaust gas diluent reduces the combustion temperature. In the latter, ignition is initiated by promoting special low-temperature combustion reactions either in the absence of a spark or initiated by a spark (spark-assisted HCCI).

Due to the exponential effects of temperature on combustion rate, both of these combustion modes can be highly unstable. Previous research has documented that these instabilities can propagate between successive engine cycles via feedback of species and thermal energy in the residual exhaust gases. In this work, we show two examples of how this feedback leads to long-term persistent bistable combustion modes superimposed on shorter-term cyclic oscillations.

In certain parametric ranges of high EGR operation, the engine can alternate between many (10s) cycles of successive strong combustion and many (10s) consecutive cycles of misfires (with little or no combustion). We illustrate experimental variations in the long-term cycle frequency with EGR loop length and propose a physical mechanism to explain this behavior. We also discuss the practical implications for engine operation.

In engines operating near the boundary between spark-ignited combustion and spark-assisted HCCI, the combustion can spontaneously switch between persistent modes of spark-dominated and HCCI-dominated states, forming a long-term cycle. We illustrate experimental examples of this behavior, propose a possible mechanism, and comment on the practical implications.

Improved control of these long-term bistabilities is critical to realize the potential benefits in fuel economy and reduced emissions that high EGR and HCCI offer. Understanding the underlying mechanisms and identifying realistic control options will be key to meeting performance targets set by engine manufacturers and the U.S. Government. Additionally, we expect that similar instabilities may occur in other systems. Thus the diagnostics and control strategies developed for advanced engines might have value elsewhere.

P.25

Computation of quasiperiodic solutions to the Kuramoto-Sivashinsky equation

Adam Fox and Predrag Cvitanović

Georgia Institute of Technology

The Kuramoto-Sivashinsky Equation (KSE) arises in the study of interfacial instability in a variety of settings such as flame-front propagation and the liquid film on an inclined plane. When only a single spatial dimension is considered the system can be parameterized by the length of the corresponding interval. As the spatial domain increases, the orbits of the Kuramoto-Sivashinsky system become increasingly turbulent. Quasiperiodic solutions are theorized to exist within this turbulence. These solutions lie on invariant tori which act as barriers to transport and are therefore of significant dynamical importance. In this poster I will present a numerical method to compute such orbits and describe its application.

Happiness and the patterns of life: A study of geolocated tweets

Morgan Frank, Lewis Mitchell, Peter Sheridan Dodds and Christopher M. Danforth

University of Vermont

The patterns of life exhibited by large populations have been described and modeled both as a basic science exercise and for a range of applied goals such as reducing automotive congestion, improving disaster response, and even predicting the location of individuals. However, these studies have had limited access to conversation content, rendering changes in expression as a function of movement invisible. In addition, they typically use the communication between a mobile phone and its nearest antenna tower to infer position, limiting the spatial resolution of the data to the geographical region serviced by each cellphone tower. We use a collection of 37 million geolocated tweets to characterize the movement patterns of 180,000 individuals, taking advantage of several orders of magnitude of increased spatial accuracy relative to previous work. Employing the recently developed sentiment analysis instrument known as the hedonometer, we characterize changes in word usage as a function of movement, and find that expressed happiness increases logarithmically with distance from an individual's average location.

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P.27

Is it possible to predict the risk of sudden cardiac death?

Leon Glass, T. D. Quail and A. Shrier

McGill University, Montreal

The transition from normal sinus rhythm to fatal arrhythmias is of both theoretical and practical interest. We are studying dynamic transitions in cardiac tissue culture with a view of better understanding the mechanisms that are relevant in the clinic. In addition we are studying complex rhythms in humans with a goal of learning how to better decode the complex rhythms present. I believe that the answer to the question I pose is yes, but I still do not know how to do it. I hope to encourage experts in dynamics to think about the problem also.

P.28

Design considerations for a high-capacity chaotic communications channel

Sidni Hale, A N Beal, J P Bailey, R N Dean, J K Tugnait, N J Corron and M Hamilton

Auburn University

A simple, high frequency (HF), mixed signal chaotic oscillator has been realized in hardware. This oscillator topology exhibits advantages of both linear and nonlinear systems due to its closed form solution. Novel low frequency (LF) oscillators (700Hz-2kHz) exhibiting exactly solvable, chaotic behavior have been previously realized in hardware [3]. However, the generation of low frequency signals has limited applicability in fields such as Communications. These limitations motivate the development of similarly solvable, chaotic oscillators that operate in high HF bands (>1MHz). The nonlinear dynamics of such chaotic systems provide interesting, real world advantages to engineering applications which are inherent to systems exhibiting these nonlinearities. Such advantages from nonlinear chaotic systems include synchronization, the spreading of spectral components, truly random number generation and the ability to obfuscate information encoded using the Hayes approach [1]. Furthermore, it has been shown that symbolic information encoded with oscillators of this topology may be extracted accurately and elegantly through means of a simple, low-cost matched filter [2]. With an increase in operational frequency shown successfully in hardware, this technology provides elegant, low-cost solutions which envelop a broader range of applications. The design, improved simulation and testing of a 1.6MHz exactly solvable, chaotic oscillator capable of offering performance comparable to traditional linear systems is subsequently presented.

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P.29

Towards reservoir computing with autonomous Boolean networks

Nicholas Haynes, David P. Rosin, Damien Rontani and Daniel J. Gauthier

Duke University

We present our preliminary work developing a reservoir computing platform using field-programmable gate arrays (FPGAs), with the ultimate goal of detecting features of complex systems. We show that the three basic properties required for reservoir computing, namely that different input states are mapped to different reservoir states, input states that are close together are mapped to identical reservoir states, and a fading memory, can be realized even in moderately-sized Boolean networks synthesized on an FPGA. The networks are realized as ring oscillators consisting of multiple-input XOR gates that accept an input (Boolean) voltage and time-delayed feedback. These oscillators exhibit long chaotic transients when the input voltage is flipped, and it is found that these transients offer promising dynamics for reservoir computing.

We gratefully acknowledge the financial support of the U.S. Army Research Office Grant W911NF12-1-0099 and National Science Foundation IGERT Grant DGE-1068871.

P.30

Resolving the state space of noisy chaotic maps

Jeffrey Heninger, Predrag Cvitanović and Domenico Lippolis

Georgia Institute of Technology

The finest resolution that can be achieved in any real chaotic system is limited by the presence of noise. This noise can be used to define neighborhoods of the deterministic periodic orbits using the local eigenfunctions of the Fokker-Planck operator and its adjoint. We extend the work of D. Lippolis [1, 2] to include hyperbolic periodic orbits. The dynamics along the stable and unstable directions are separated. The neighborhoods on the stable and unstable manifolds can be defined in the same way as the neighborhoods for entirely stable or entirely unstable orbits. The neighborhoods are then returned to the original coordinates. The Fokker-Planck evolution can be described as finite Markov transition graph between these neighborhoods. Its spectral determinant is used to calculate the time averages of observables. We apply this technique to calculate the spectral determinant of the Lozi map and compare it to the result found using Ulam's method.

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P.31

Invariant densities for dynamical systems with random switching

Tobias Hurth and Yuri Bakhtin

Georgia Institute of Technology

We consider a non-autonomous ordinary differential equation on a smooth manifold, with right-hand side that randomly switches between the elements of a finite family of smooth vector fields. For the resulting random dynamical system, we show that Hörmander type hypoellipticity conditions are sufficient for uniqueness and absolute continuity of an invariant measure.

P.32

Dynamics of Purkinje fiber conductivity

Yanyan Ji and Flavio Fenton

Georgia Institute of Technology

Purkinje fibers are essential in maintaining the heart contraction due to their fast conductivity of Action Potentials (AP). This property requires us to develop new models for Purkinje fibers different from traditional ventricular tissues. Although there are some models that can describe part of the features of the Purkinje fiber, they fail to reproduce the correct dynamics of alternans observed in experiments. Here we propose a model for a 1D Purkinje cable. We will show that by correctly setting the conductivity as a function of the transjunctional voltage, we can get both concordant and discordant alternans in a Purkinje fiber with a length comparable to experimental results.

P.33

Dynamics of leaf interacting with falling raindrops

Sunghwan Jung and Sean Gart

Virginia Tech

We investigate a leaf-drop system exhibiting a unique system of coupled elasticity and drop dynamics. To understand the effect of surface properties and beam length, water droplets impact on an elastic cantilever beam of various lengths with a wettable and non-wettable surface. We found that wettable beams experience much higher torque and bending energy than non-wettable beams. This is because a drop sticks to a wettable beam while a drop rolls off of a non-wettable beam. Simple models using energy and momentum balances explain the bending energy and torque experienced by wettable and non-wettable beams. It may elucidate the potential damage on a leaf and the effect of surface property due to raindrops.

P.34

Two Theta neuron: Phase models for bursting activity in multifunctional central pattern generators

Aaron Kelley and Andrey Shilnikov

Georgia State University

We propose and examine reduced models for multiple patterns of activity occurring in the 3-cell central pattern generator (CPG) of bursting neurons. Successful comparison to detailed Hodgkin-Huxley models of such CPG are made for a few exemplary cases including continuous transitions from the symmetric to various asymmetric circuits. Each CPG is shown to associate with a Poincaré return map with stable fixed points and invariant circles corresponding to robust bursting patterns with phase-locked and periodically varying phase lags that bifurcate as the circuit wiring is changed.

P.35

A long-wave model for strongly anisotropic growth of a crystal step

Mikhail Khenner

Western Kentucky University

A model of morphological evolution of a single growing crystal step is presented. Via a multi-scale expansion, we derived a long-wave, strongly nonlinear, and strongly anisotropic evolution PDE for the step profile, performed the linear stability analysis and computed the nonlinear dynamics. Linear stability depends on whether the stiffness is minimum or maximum in the direction of the step growth. It also depends nontrivially on the combination of the anisotropy strength parameter and the atomic flux from the terrace to the step. Computations show formation and coarsening of a hill-and-valley structure superimposed onto a large-wavelength profile, which independently coarsens. Coarsening laws for the hill-and-valley structure are computed for both orientations of a maximum step stiffness, the increasing anisotropy strength, and the varying atomic flux.

P.36

Integrating nonlinear dynamical systems by stepping through space and time

Behnam Kia, John Lindner and William Ditto

University of Hawaii at Manoa

Many conventional techniques for numerical integration of dynamical flows in nonlinear dynamics step in independent variable, typically time. And sometimes these techniques are equipped with an adaptive or variable mechanism to regulate the time step size in order to control the corresponding change in the spatial dependent variable. Here we argue the position: Why not simply step the dependent variable directly (while inferring the step in the independent variable indirectly)? We systematically study and investigate the consequences of stepping in space and time, and we introduce very simple dependent-variable based steppers that are computationally as simple as the Euler method, but they can also solve nonlinear systems that the Euler method fails to solve with a reasonable step size. Furthermore, we introduce a few examples and argue that for these systems, the new technique better describes the physics of the systems.

P.37

Bifurcation-cascade diagram of an external-cavity semiconductor laser: Experiment and theory

Byungchil Kim, Nianqiang Li, A Locquet and D S Citrin

Georgia Tech Lorraine

The dynamics of external-cavity semiconductor lasers (ECSL) are known to be complex and difficult to control; in view of the rich dynamical behavior as well as the technological importance of these devices, their dynamics have been widely investigated. Until a few years ago, this chaotic behavior of semiconductor systems was viewed as an unwanted irritation to be engineered away. Nowadays, rather than simply being avoided, such dynamical instabilities are of intense interest for applications, such as secure communications, light detection and ranging (LIDAR), random-number generation, and reservoir computing. Even though there are numerous studies of the dynamics of ECSLs in restricted regimes, yet a comprehensive picture-and on that reconciled experiment and theory across a range of operating parameters-remained, surprisingly, until now unavailable. Since bifurcation diagrams (BD) provide a standard way within the nonlinear-dynamics community to visualize the dependence of the dynamical regime on a control variable, experimental BDs for Er-doped fiber lasers, optically injected solid-state lasers, and gas lasers have been mapped out. Nevertheless, there is an almost total lack of experimental BDs available for ECSLs because there are several experimental hurdles we have overcome that need no necessarily be resolved for more restricted studies. Despite these difficulties, there is a need for such measurements as they provide a way to test the reliability of models for the laser dynamics, such as the Lang-Kobayashi (LK) model. We report experimental BDs of an ECSL focused on the case of an ECSL biased just above threshold to moderate currents (2-3 times threshold) and subjected to feedback from a near/distant reflector, which is particularly well-suited for chaos-based communication, and observed a sequence of bifurcations involving limit-cycles, quasi-periodic and period-doubled behaviors, as well as intermittency between multiple coexisting attractors. Importantly, we reiterate: the results map out, for the first time to our knowledge, detailed BDs of ECSL as function of feedback strength for various external cavity lengths and currents, thus covering a significant portion of parameter space. We have grounded our discussion in extensive theoretical studies based on the LK equations and simulated BDs in accordance with our experimental results.

P.38

Surface-tension-induced motion of an elliptic camphor particle

Hiroyuki Kitahata, Keita Iida and Masaharu Nagayama

Chiba University

The coupling between deformation and motion in a self-propelled system has attracted broader interest [1], especially in the field of "active matter". In order to investigate the features of such interaction, the effect of the particle shape on the direction of motion is focused. We consider a model system in which surfactant molecules diffuse from the particle and reduces the surface tension around the particle. The symmetric concentration profile of the surfactant molecules can exhibit spontaneous symmetry breaking, which leads to a one-directional motion. In fact, a circular camphor particle floating at water surface can exhibit spontaneous motion while it diffuses surface-active camphor molecules to the water surface [2]. In the present study, thus, we adopt the camphor-water system. As for the particle shape, we focus on the most fundamental but nontrivial deformation from a circle, i.e., an elliptic shape. Therefore, we consider an elliptic camphor particle which diffuses camphor molecules for investigating the effect of the particle shape on spontaneous motion. We analytically calculated the force exerted on the camphor particle using the perturbation method. We concluded that the symmetric spatial distribution of camphor molecules at the water surface becomes unstable first in the direction of a short axis, which induces the camphor disk motion in the short direction. Experimental results also support the theoretical analysis. From the present analysis, we suggest that an elliptic particle supplying surfactant molecules to the water surface can exhibit translational motion only in the short-axis direction [3].

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P.39

Estimating connectivity and stimulus in a noisy Lotka-Volterra network

Christopher Knowlton and Henry Abarbanel

UCSD

Information in neural networks is frequently represented in firing rate patterns among individual or clusters of neurons networked together with inhibitory and excitatory synaptic connections [1]. This information is thought to be represented through fixed points and limit cycles with deterministic switching from one saddle point mode in response to changes in the stimulus.

An activity based model of network dynamics allows for a simplification over spiking neuron models to capture longer timescale behavior with a reduced dimensional model. For this poster we will be working with the a 3 state Lotka-Volterra model [2] that describes the time evolution of the firing rate - x(t) of each of the three network nodes in response to mutual feedback and excitatory stimulus S(t) and stochastic excitatory and inhibitory currents η^+ and η^-.

$$\dot{x}_i = x_i \left[\sigma_i(S_i, \mathbf{x}, \eta^+(t)) - x_i - \textstyle\sum_{j\neq i} \rho_{ij} x_j + \eta^-(t)\right]$$

$$\sigma_i = \tanh\left[5\left(g_E \textstyle\sum_{j\neq i} x_i - 0.4 + S_i + \eta^+(t)\right)\right]$$

In an actual system, the connections between the nodes would be unknown - requiring estimation of the elements of the inhibitory connectivity matrix - ρ_{ij} and excitation g_E. In a fully controlled systems, we would have access to information about the stimulus applied to the network - potentially via activity measurements of the sensory layers. However for a system in which this information is not available or the source of the stimulus is not well understood, the stimulus to the network must also be taken to be an unknown quantity. Information about the system can be obtained through extracellular spike timing measurements in each of the nodes - allowing for the potential of simultaneous measurements of all the dynamical variables in the system.

In prior work [3–5] we have demonstrated that a path integral method with an action developed from the dynamical transition probabilities and conditional mutual information between the measurements and states can be used to estimate unmeasured states and parameters in non-linear systems provided measurements of a subset of the dynamical variables. We will consider a simulated experiment on a simple Lotka-Volterra network with measured activity and unknown stimulus and connectivity. We will estimate the unmeasured stimulus and model parameters conditioned on measurements of the activity of each of the three model nodes. We demonstrate that fairly accurate estimates of connectivity parameters and stimulus information can be achieved simultaneously despite the presence of multiplicative model noise.

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P.40

Multiplicity of singular synchronous states in the Kuramoto model of coupled oscillators

Maxim Komarov and Arkady Pikovsky

Potsdam University

We study the Kuramoto model of globally coupled oscillators with a bi-harmonic coupling function. We develop an analytic self-consistency approach to find stationary synchronous states in the thermodynamic limit. We show that (i) there exist synchronous regimes *prior* to the stability threshold of the desynchronized state; (ii) these regimes have order parameters that can take values anywhere in the range $(0, R_{max}]$ for some $R_{max} < 1$; (iii) there is a huge multiplicity of these states for fixed coupling parameters, we estimate their number as growing exponentially with N; (iv) when a small noise is added, the multiplicity is lifted, but a nontrivial synchronous regime coexists with the stable asynchrony.

P.41

Bifurcation analysis on self-driven particle motion in a 1-d finite region

Yuki Koyano, Hiroyuki Kitahata and Tatsunari Sakurai

Chiba University

Self-driven motions have been paid more and more attention to in terms of "active matter", where free energy is transformed into kinetic energy. A camphor grain at water surface is a famous example of the self-driven particles. If a camphor grain is floated on the water, camphor molecules spread at water surface and reduce the surface tension because they work as surfactants. If the concentration field has anisotropy around the camphor grain, then surface tension also has anisotropy. Thus, the camphor grain is driven in the direction with the largest surface tension. To summarize, the camphor grain releases latent heat with sublimation, and the part of which transforms into kinetic energy.

In this system, the interaction between a particle (a grain) and field is important. The camphor grain affects the camphor concentration field through dissolution and diffusion from the grain position, while anisotropy of surface tension (corresponding to anisotropy of the concentration field) drives the camphor grain. Thus, the field boundary can affect the camphor grain motion through the field.

In the previous works, the self-driven particle in the 1-dimensional infinite region is investigated analytically and experimentally [1]. In this study, to clarify the boundary effects, we have analytically investigated what motion can be exhibited when a self-driven particle is put in a 1-dimensional finite region. We found that oscillating motion appears as a final state in a finite region instead of uniform motion in an infinite region. This is because the translational symmetry is broken in the finite system.

In the finite system, the center position is a fixed point; If a camphor grain is located at the center of the system, the concentration field will be isotropic and the sum of the force working on the camphor grain will be zero. If a camphor grain is slightly off from the system center, in contrast, the camphor is driven by the surface tension. After long time evolution, the camphor grain should rest at the center if the fixed point is stable, while the camphor grain should oscillate if the fixed point is unstable. We found that the particle motion changes from rest at the system center into oscillation around it when a parameter such as the system size or viscosity is decreased. In other words, the stability of the center position is depending on parameters. This change in particle motion can be understood as a bifurcation in terms of applied mathematics. We have obtained the bifurcation structure around the fixed point by reducing the fundamental equations around the center position of the system.

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P.42

Separation of DNA by length in rotational flow

Jennifer Kreft Pearce and Faihan Alfahani

Roger Williams University

We use a lattice-Boltzmann based simulation to investigate using counter-rotating vortices to separate DNA of different lengths. Rotating fluid flow has been used to concentrate DNA as well as separate colloidal particles of different sizes in experiments. We want to explore combining the two experiments in simulation to determine if vortices can be used to separate DNA of different lengths. The model we use has been shown to be equivalent to the Navier-Stokes equations for fluid flow in systems such as the ones we are studying with low Mach and Knudsen numbers. For DNA, we use a bead spring model which has been parametrized to mimic lambda-phage DNA. The DNA is composed of beads connected by nonlinear springs. The beads can interact with the fluid via the viscous force and a Brownian force that produces diffusion. This interaction can also perturb the fluid leading to hydrodynamic interactions between the beads.

We have found good separation when the lengths of two DNA molecules are differ by 50

P.43

Atrial myocyte model parameter identification via dynamic electrophysiology protocols and automated search algorithms

Trine Krogh Madsen, Margo Smith and David J Christini

Weill Cornell Medical College

Atrial fibrillation is an increasingly common sustained cardiac arrhythmia with serious morbidity and mortality. Because atrial fibrillation has several variants, is multi-factorial, and evolves over time, it is very difficult and expensive to study comprehensively clinically or in animal models. Predictive multiscale computational modeling has the potential to fill this research void. The foundation of a realistic multiscale heart model is only as strong as the underlying cell model. While there have been myriad advances in the improvement of cellular-level models, the identification of model parameters, such as ion-channel conductances and rate constants, remains a challenging problem. A main limitation is that such parameters are usually estimated from data recorded using standard electrophysiology voltage clamp protocols that have not been developed with model building in mind. We will describe our recent efforts to improve model parameter identification by combining dynamically rich electrophysiology protocols with automated computational search methods. We aim to use such an approach to develop patient-specific atrial cell models and incorporate those into atrial structures based on patient CT scans to improve the fidelity of our multiscale human atrial model.

P.44

War and peace in animal society

Edward Lee, Bryan C Daniels, David C Krakauer and Jessica C Flack

University of Wisconsin

We study the dynamics underlying conflict generation in a society of pigtailed macaques, a species of monkey. Conflict, as a part of social decision making in this society, is a complex, collective process that depends on time and the identity of participants. Despite these complications, the aggregate distributions of waiting times between fights and the lengths of fights converge to simple statistical limits. Thus, we propose simple models that similarly generate these distributions and relate their parameters back to known behaviors in the group, where we know the underlying social structures.

P.45

Density-based and transport-based core-periphery structures in networks

Sang Hoon Lee, Mihai Cucuringu and Mason A Porter

University of Oxford

Networks often possess mesoscale structures, and studying them can yield insights into both structure and function. It is most common to study community structure, but numerous other types of mesoscale structures also exist. In this talk, we examine core-periphery structures based on both density and transportation [1]. In such structures, core network components are well-connected both among themselves and to peripheral components, which are not well-connected to anything. We examine core-periphery structures in a wide range of examples of transportation, social, and financial networks—including road networks in large urban areas, a rabbit warren, a dolphin social network, a European interbank network, and a migration network between counties in the United States. We illustrate that a recently developed transport-based notion of node coreness is very useful for characterizing transportation networks. We also generalize this notion to examine core versus peripheral edges, and we show that this new diagnostic is also useful for transportation networks. To examine the properties of transportation networks further, we develop a new family of generative models of road-like networks. We illustrate the effect of the dimensionality of the embedding space on transportation networks, and we demonstrate that the correlations between different measures of coreness can be very different for different types of networks.

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P.46

Extracting connectivity of networks from dynamics

Chung Yin Leung and Emily S. C. Ching

The Chinese University of Hong Kong

The study of networks has become increasingly important in many disciplines. The knowledge of how the different nodes of a network interact or connect with one another is crucial for the understanding of the collective behavior and the functionality of a network. Therefore, finding a method to extract the connectivity of an unknown network from measurements is of immense research interest. This problem is highly challenging and existing methods have various limitations. For example, methods using statistical correlation between the measurements of two nodes do not necessarily give correct physical connectivity of the nodes. Other methods require information in addition to the measurements of the dynamics of the nodes like the response of the network to various perturbations, the functional form of the interactions or the coupling strength of the interaction, and such information is difficult to obtain in realistic situations. We have recently developed [1] a method that extracts the network connectivity using only measurements of the dynamics of the nodes for bidirectional networks with uniform coupling strength. Our method is built upon a noise-induced relation between the Laplacian matrix L_{ij} of the network and the pseudoinverse of the dynamical covariance matrix C^+_{ij} of the nodes i and j [2]:

$$L_{ij} = \frac{\sigma^2}{2g} C^+_{ij} \tag{P.46.1}$$

where σ is the noise amplitude and g the coupling strength. This relation is exact for the consensus dynamics with linear diffusive coupling. Our method of extraction is based on the separation of $r_{ij} \equiv C^+_{ij}/C^+_{ii}$, for each node i, into two groups depending on whether node j is connected to node i or not. Such a separation is guaranteed by eq. (P.46.1) for the consensus dynamics, and has been found even in networks with nonlinear dynamics. Using examples of different networks and dynamics, we have demonstrated that our method can give accurate connectivity information for a wide range of σ and g, and can successfully extract the global network properties of the degree distribution and the eigenvalue spectrum of the adjacency matrix. In this talk, we shall discuss our method and the results of our study.

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Part III

Poster Session B - 3:40PM to 5:10PM Saturday, January 4

P.1

Impact of a vertical vibration on a long-wave Marangoni convection

Mikhail Khenner

Western Kentucky University

We study the impact of a monochromatic vertical vibration on a nonlinear evolution of a layer heated from below. A wide range of the vibration frequency is analyzed, which allows us to describe a broad spectrum of phenomena, from parametric excitation to averaged dynamics. The dynamics depends strongly on the thermal properties of the substrate and the heat flux to the ambient. The latter is modeled by the Newton law of cooling with the appropriate Biot number. Two opposite limits are analyzed: (i) a substrate of high thermal conductivity and a finite Biot number at the free surface; (ii) an almost thermally insulated layer: the heat conductivity of a rigid wall is low and the Biot number at the free surface is small. First we consider high vibration frequency, which means that the vibration period is small in comparison with the typical time of relaxation of a longwave disturbance. Therefore, the averaged description developed in [1] is extended to the heated film. For the case (i) it is shown that the averaged vibration-induced term coincides with the one which was found in [1]; in particular, when the frequency is ultra-high (such that the viscous layer is thin in comparison with the layer thickness) the amplitude equation from [2] is reproduced. In contrast, for the case (ii) the nonuniformity of the oscillatory part of the temperature is also important and the set of two amplitude equations is derived. In the particular case of the vibration turned off, this model reduces to the one in [3]. When the frequency is ultra-low, the typical time of the relaxation of the layer thickness is comparable with the vibration period. In this situation the vibration results only in the gravity modulation within the model appropriate for each case: the standard generalized Cahn–Hilliard equation [4] for the case (i) and the set of amplitude equations from [3] for the case (ii). We also derived the intermediate asymptotics showing the transition from high to ultra-low frequency. Finally, we confirmed the conclusion of [2] that there is no coupling of a slow Marangoni convection and a fast Faraday instability. S.S. acknowledges the financial support by RFBR within the Grant 13-01-96010.

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P.2

Nonlinearity and programmability: Utilizing nonlinearity to build reconfigurable computation

Behnam Kia and William Ditto

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The interrelationship between nonlinearity and programmability is studied and it is shown that the more chaotic a system is, the more reconfigurable and flexible the system will be for computation. It is believed that the flexibility of natural and living systems and their ability for adaptation and coping with different conditions originates from nonlinearity. Even the nature of artificial systems that we engineer or synthesize, e.g. a transistor, is nonlinear as well. But it seems that the nonlinearity hasn't been utilized in engineered systems to its full extent.

Here we focus on nonlinear dynamics, explain how digital computation can be implemented based on it, then measure its functionality in terms of how many different digital function the system can implement, and at the end study how the amount of dynamical system's nonlinearity and unpredictability in behavior is connected to functionality of the system.

P.3

Multistability in the Lorenz system

Chunbiao Li and J. C. Sprott

Southeast University

The Lorenz system is one of the most widely studied of the many chaotic systems now known, and it is the prototypical example of sensitive dependence on initial conditions (the butterfly effect). For the standard parameters used by Lorenz, there is a single symmetric double-wing chaotic attractor that resembles a butterfly. In this paper, the dynamical behavior of the Lorenz system is examined in a previously unexplored region of parameter space, in particular where r is zero and b is negative. For certain values of the parameters, the classic butterfly attractor is broken into a symmetric pair of strange attractors, or it shrinks into a small attractor basin intermingled with the basins of a symmetric pair of limit cycles, which means that the system is bistable or tristable under certain conditions. This multistability may have not obvious physics meaning of fluid convection, however it may be associated with some other physical systems as well as their application since the Lorenz equations have been used to model other systems, such as lasers, dynamos, thermosyphons, waterwheels, and chemical reactions.

P.4

Nonequilibrium steady-states for particle systems

Yao Li and Lai Sang Young

New York University

We rigorously investigated nonequilibrium steady states for a class of particle systems coupled to unequal heat baths. These stochastic models are derived from the mechanical chains studied by Eckmann and Young by randomizing certain quantities while retaining other features of the model. Our results include the existence and uniqueness of nonequilibrium steady states, their relation to Lebesgue measure, tail bounds on total energy and number of particles in the system, and exponential convergence to steady states from suitable initial conditions.

P.5

Exact coherent structures in models of cardiac tissue

Christopher Marcotte and Roman Grigoriev

Georgia Institute of Technology

Excitation waves in the heart generate contractions by stimulation of the underlying tissue. A variety of destabilizing mechanisms destroy normal heartbeat rhythm, generating more complex wave patterns. This transition, generically from pulse excitations to spiral waves and finally spatiotemporal chaos, is an extensively studied phenomenon corresponding to pulsatile rhythm, tachycardia, and fibrillative regimes in the heart.

Our objective is to construct a description of spatiotemporally chaotic cardiac rhythms in terms of recurrent patterns (also known as exact coherent structures) that correspond to exact unstable regular solutions of the evolution equations and use these solutions and their heteroclinic connections to guide the dynamics through phase space, e.g., from fibrillation to normal rhythm.

Continuous symmetries (rotations and translations) in extended cardiac tissue complicate the search for coherent structures, generating localized features which inherit the global symmetries of the system. Here we describe the computational approach for identifying several classes of exact solutions in two dimensional models of cardiac tissue: relative equilibria which are associated with isolated spirals with fixed cores and relative periodic orbits which describe isolated spirals with drifting cores.

P.6

Dynamics and control of cardiac tissue

Greg Byrne, Chris Marcotte and Roman Grigoriev

Georgia Tech

Cardiac arrhythmias are characterized by abnormal dynamics that occur during the activation of excitable cardiac tissue. Ventricular tachycardia and ventricular fibrillation - a life threatening chaotic regime associated with cardiac arrest - are both examples of arrhytmias characterized by spiral wave-dominated dynamics.

Our research seeks to restore normal rhythm by applying novel, low-energy methods of control for cardiac tissue. The proposed method is underpinned by a description of spatiotemporally chaotic dynamics in terms of recurrent patterns that correspond to exact unstable regular solutions of nonlinear reaction-diffusion models of cardiac tissue.

Numerical methods originally developed in the context of fluid turbulence have enabled us to identify two classes of such regular solutions: relative equilibria which are associated with isolated spirals with fixed cores and relative periodic orbits which describe isolated spirals with drifting cores. These two classes of solutions arise due to the global rotational and translational symmetries of the underlying evolution equations. In order to find regular solutions featuring multiple interacting spirals a new approach is needed that takes into consideration the dynamics of slowly drifting cores associated with local, rather than global symmetries.

We describe recent efforts to understand local symmetries in terms of pairwise interactions between spiral cores. The ability to understand and reduce local symmetries provides an important first step towards classifying and computing the unstable time-dependent solutions that organize spatiotemporally chaotic dynamics of cardiac tissue.

P.7

Reversing desertification: a pattern-formation approach

Yair Mau, Lev Haim and Ehud Meron

Duke University

Climatic variations and human activity can cause reduction or loss of biological productivity, a process which is called *desertification*. Quite often, when environmental conditions return to their previous state, the vegetation is unable to recover spontaneously, because of the multiple stability of unproductive and productive states. In recent years there has been much interest in studying the rehabilitation of damaged ecological systems. The first step of rehabilitation is recovery of vegetation, which can be achieved in drylands by harvesting rain water in hill slopes. A common water-harvesting practice is the construction of parallel contour ditches – termed *shikim* – which accumulate runoff water from the uphill areas, and along which trees are planted.

An important factor in the success of rehabilitation in this kind of practice is the fact that vegetation in water limited regions can self-organize in patterns. Water is the most constraining resource for those systems, and the patterns formed can be the result of several positive feedbacks between the biomass and water. The feedbacks are responsible for redistributing water in the system, which breaks spatial symmetry and can lead to the formation of patterns.

Because undisturbed natural systems in drylands can form patterns with a typical wavelength, the shikim technique can be understood as spatial periodic forcing applied to a pattern forming system. The parallel tree lines planted along the contour ditches constitute a resonant solution of the system, whose typical wavenumber is *locked* in a 1:1 resonance with the forcing wavenumber.

We develop a simple vegetation model for water-limited systems, and introduce to it spatial periodic forcing that imitates the role of the parallel ditches. We find two kinds of wavenumber-locked solutions: stripe patterns in a $1:1$ resonance with the forcing wavenumber, and rectangular patterns in a $2:1$ resonance. We investigate the stability ranges of these two solutions, and it is shown that the rectangular pattern, being more *resilient* than the stripe pattern, has greater capability in reversing desertification.

We also study a much simpler pattern-forming system – the Swift-Hohenberg equation – subjected to spatial periodic forcing. From the derived amplitude equations we are able to find the same stripe and rectangular solutions of the vegetation model. The analysis elucidates the mechanisms by which the rectangular solution is more resilient than the stripe solution, corroborating the findings of the vegetation model that the rectangular solution is a preferable configuration for the recovery of vegetation in drylands.

P.8

Noise amplification and propagation in biochemical networks

Jonathan McCoy, John Dixon and Anika Lindemann

Colby College

Fluctuations are known to be a conspicuous feature of gene regulatory systems. A protein expressed by any particular gene influences the expression of many other proteins through a complex network of regulatory interactions and, because of this network, fluctuations in expression levels can propagate throughout the system. Determining how these fluctuations are tolerated, controlled, or exploited by different network architectures is a cross-disciplinary challenge with far-reaching consequences. The question of whether propagation implies amplification of noise, for example, impacts our understanding of the origins of observed noise levels. Note that amplification does not require instability. Building on this insight, which has a long history in fluid dynamics and ecology, we suggest a alternative framework for exploring the principles governing noise in gene regulatory networks. In particular, by analyzing the amplification properties of various network motifs, we can extract valuable knowledge about the amplification properties of a system as a whole.

P.9

Three-dimensional tracking of nanoparticles in superfluid helium

David Meichle and Dan Lathrop

University of Maryland

Liquid Helium becomes a quantum superfluid when cooled below the lambda transition temperature of 2.17 Kelvin. Superfluid helium is characterized by interesting macroscopic effects such as vanishing viscosity, and its flow is irrotational except for the presence of line-like topological phase defects with quantized circulation called quantum vortices. The quantized vortex dynamics can be observed by dispersing tracer particles into the fluid which become trapped on the vortex cores. Interesting flow states and vortex dynamics including the formation of a vortex lattice in rotating superfluid and the excitation of self-similar propagating helical Kelvin waves on the vortex cores have been observed previously in 2D using frozen ice particles. Observation of these intrinsically three dimensional phenomenon has motivated the development of a three dimensional imaging apparatus. We will present new data obtained by dispersing nanometer sized fluorescent tracer particles, and our progress towards full three dimensional tracking of quantized vortex dynamics in liquid helium.

P.10

Haploid and diploid recombination and their evolutionary impact

William Mitchener

College of Charleston

Genetic recombination allows a species to mix and match genes already present in the population, so as to quickly discover beneficial combinations. This poster will show the results of an evolutionary simulation in which two recombination mechanisms are compared. Simulated organisms are called *agents* and consist of artificial regulatory networks called Utrecht machines. Agents are rated on how well they solve a communication problem. Selective breeding eventually finds a perfectly scoring agent. The simulation can be configured to use haploid recombination, similar to what occurs in bacteria, or diploid recombination, similar to what occurs in sexual reproduction. Perfect solutions found using haploid recombination tend to be smaller and are found more quickly on average. Diploid recombination increases the likelihood that agents with lower ratings than the current maximum will yield a child whose rating exceeds the current maximum. The choice of recombination mechanism also has a complex influence on genetic diversity.

P.11

Forecasting cardiac arrhythmias with a one-dimensional fiber model

Laura Munoz, Niels F. Otani, Anna R. M. Gelzer, Flavio H. Fenton, Wei Lin, Min Chul Shin and Robert F. Gilmour

Rochester Institute of Technology

Ventricular fibrillation (VF) is a lethal, uncoordinated cardiac rhythm that is sometimes preceded by a short sequence of premature, irregularly-timed beats. To gain an improved understanding of the relationship between premature beats and VF formation, a 1D nonlinear dynamical model of electrical wave propagation was developed. In this model, the duration of an electrical wave and the wavefront speed are approximated as nonlinear functions of the preceding resting interval between waves. This model has allowed us to investigate a proposed mechanism for VF induction, where certain sequences of premature beats induce spatial and temporal alternations in wave duration, which in 2D and 3D geometries can eventually degenerate into the disorganized propagation and circulating patterns that are characteristic of VF. In previous studies, the 1D model was shown to predict which sequences of premature beats were more likely to produce VF in canine hearts *in vivo*. The more recent phase of the study has focused on comparing the predictions of the model with more detailed observations obtained from *in vitro* cardiac data sets. We applied a likelihood ratio test to logistic regression results to confirm that the effect of the model prediction is significant ($p < 0.0001$, coeff. 1.26, n = 184 sequence categories) *in vitro*. We also determined that the predicted spatial changes in wave duration are positively correlated with the observed values, which provides evidence in favor of the proposed mechanism. These results are encouraging, and may serve as a basis for developing improved methods for anticipating and preventing VF.

P.12

Nonlocally coupled chemical oscillators in a ring configuration

Simbarashe Nkomo, Mark R Tinsley and Kenneth Showalter

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Synchronized and mixed state behaviors are observed in populations of chemical oscillators in a ring configuration. With nonlocal coupling, the nearest neighbors are strongly coupled and the coupling strength decreases exponentially with distance. Experiments are carried out with photosensitive Belousov-Zhabotinsky chemical oscillators and a light feedback scheme. The dimensionless two-variable ZBKE model of the chemical system is used in simulations. We report experimental studies of the chimera states, phase cluster states and phase waves coexisting with unsychronized groups of oscillators. The effects of group size, heterogeneity, and coupling strength on chimera states, phase waves, phase clusters, and traveling waves are discussed. Complex behavior in coexisting states is analyzed, including periodic states observed in both identical and nonidentical oscillators.

P.13

Designing a self-propelling microswimmer using a bi-faced hydrogel

Svetoslav Nikolov, Peter Yeh and Alexander Alexeev

Georgia Institute of Technology

We use dissipative particle dynamics to design a new self-propelling polymeric microswimmer. The microswimmer is made of a gel-like material formed from two thin layers of polymer networks with distinct properties that a bonded together. One of the layers swells and increases in volume in response to an external stimulus, whereas the other network layer is passive. The layers have identical mechanical properties and thickness. The swimmer has an X-shaped body. We show that when an external stimulus is periodically imposed, the swimmer propels itself unidirectionally in a highly viscous fluid. This propulsion is caused by periodic shape changes of the swimmer. When the stimulus is applied, the responsive layer swells, inducing internal stresses in the nonresponsive layer causing microswimmer bending. When the external stimulus is removed, the responsive layer contracts, and elastic forces cause the microswimmer to straighten. In addition to bending, the swimmer also expands outwards. The combination of the sequential bending and expansion produces a time irreversible motion leading to net propulsion in a low Reynolds number environment. In our simulations, we examine the swimming velocity and determine the criteria for maximizing swimming speed.

P.14

A coupled multiple-ring model of far-field cardiac defibrillation

Niels Otani

Rochester Institute of Technology

Fibrillation in the heart is a dynamically complex process, the details of which have defied mathematical characterization. Attempts to develop dynamically-inspired electrical defibrillation protocols have largely been stymied for this reason. Recently, we have taken steps to develop models that represent one of the most salient features of fibrillation–the presence of multiple, rotating action potential waves. In previous work, we found that, when a single wave is initiated in an isolated, coupled-maps model of a ring, a large number of far-field electrical stimulation patterns can terminate the wave irrespective of when the stimulus pattern is administered. In our current work, we have extended the model to include multiple, coupled rings, each of which contains a rotating wave. We find that the same patterns that terminate waves propagating in the individual, isolated rings are also highly successful in terminating all the waves in these multiple ring systems, with “defibrillation” occurring over 99% of the time in computer simulations involving randomized ring configurations, initial conditions and stimulus pattern initiation times. The mechanism of wave termination, which is based on discordant alternans dynamics, is an extension of the one we found in the single-ring cases. Large shifts in the wave circulation times induced by inter-ring coupling generally did not affect the defibrillation process, due apparently to the robustness of the wave termination mechanism to significant changes in these times. These results provide important new guidance for far-field defibrillation experiments currently being conducted by identifying the specific stimulus patterns that are most likely to be successful. In the longer term, creative use of the dynamical properties of the interaction between stimuli and rotating waves exposed and exploited in the current study has the potential for yielding new defibrillation therapies that require lower energy shocks that are consequently less painful, less traumatic, and less damaging to surrounding tissues than are current defibrillation protocols.

P.15

Dynamical description of 2D weakly turbulent flow using exact coherent structures

Ravikumar Pallantla, Balachandra Suri, Radford Mitchell and Roman Grigoriev

Georgia Institute of Technology

The dynamical systems picture of turbulence is an interesting and a relatively new area of study to gain insight into the dynamics of fluid flows. When a flow is weakly turbulent, it is conjectured that the evolution of the flow is governed by exact, unstable solutions of the equations governing the flow. Such solutions, called Exact Coherent Structures (ECS) have been identified using numerical simulations of 3D flows, but there is no direct experimental evidence supporting this picture.

Quasi-two-dimensional(Q2D) flows are a promising system to verify numerical predictions of ECS-based description experimentally. We investigate the dynamics of the Q2D-flow in a shallow layer of electrolyte driven electromagnetically. A computational model has been constructed for this flow with special attention given to boundary conditions, to mimic the flow in the experiment. The model has been used to compute a number of ECS numerically. We present the results of numerical simulation and compare them with available experimental data.

P.16

The dynamics of buoyant tubes growing in chemical gardens

Jim Pantaleone

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When a metal salt is placed in a sodium silicate solution then chemical gardens grow. These systems have been studied for over 300 years and are a popular chemical education activity. There has been a resurgence of interest in these systems recently because of the wide variety of shapes produced and because they may be useful for new technologies.

The most common structure in chemical gardens is an upward growing tube. A variety of mechanisms have been reported for how these tubes grow: smooth flow out of open tubes, periodic rupturing of closed tubes, bubble driven tube growth, and continuous mid-tube spreading. Also, the number of tubes growing from the cell may vary from one to a couple dozen or more. Here the dynamics of tube growth are studied in controlled, quantitative experiments.

We chose to study a system where typically only a few tubes grow at any one time. In particular, a solution of 0.50M $AlCl_3$ and 0.75M NaCl was pumped into 1.5M sodium silicate solution. For this metal salt at these concentrations upward growing tubes form with a semi-closed tube end that grows smoothly without bursting or rupturing. For single tubes, the tube size, rate of growth and pressure change with length were measured as a function of the pumping rate. It was found that these tubes tend to grow at a constant rate and that the pressure dependence is well described by the Hagen-Poiseuille law. Also, the dependence of tube size on the pumping rate obeys a power law with an exponent of 0.42 +/- 0.05. This exponent agrees with growth at a constant Richardson number. This exponent value is different than the value 0.25 which occurs for buoyant laminar plumes and open tube growth.

With these results it is possible to formulate a description of what happens when multiple tubes grow from the same chemical cell. Multiple tubes have the same cell pressure and must share the osmotic inflow. How the tubes grow depends on how well they compete for these resources. The differential equations describing this resource competition are very similar to those describing competition between animal species.

P.17

Heart phase portrait using the autocorrelation

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Heart rate variability (HRV) is necessary for sustained life. The healthy human heart never beats in a monochromatic manner; rather, the organ shows a rhythmic variability in the beat to beat intervals (BBI). The periodic cycling, between slower and faster rates than average, typically shows about six cycles per minute, known as the Mayer wave. Peak to peak variations tend to be a few percent of the average BBI. A diseased heart loses HRV when it goes into failure, and so diagnostic tools with which to readily identify its presence are valuable to the medical community. Classical phase portraits generated from an electrocardiogram reveal almost no information concerning HRV. But the autocorrelation, when calculated using the Wiener Khinchin theorem and the FFT (with proper accounting for causality) provides a heart phase portrait whose visual characteristics permit one to readily see the presence of HRV.

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P.18

Niche construction and macroscopic tuning via adaptive learning rules

Philip Poon

Wisconsin Institute For Discovery, University of Wisconsin

Many dynamical systems are organized into hierarchical structures. In this project we consider the origins of both stable and periodically stable hierarchies. We analyze two multi-scale niche construction models in which competing strategies at the microscopic level construct, via adaptive learning rules, new institutions in the macroscopic levels in order to out-perform each other. These institutions provide slow ($O(\epsilon)$), top-down feedback to the microscopic level. We demonstrate, under certain rule and parameter space, how the system can undergo Hopf bifurcation and go into a regime in which there is rapid O(1) switching between probable to improbable microscopic states, with $O(\epsilon^{-1})$ residence times between switches, without large changes at the institution level.

P.19

Predicting market instability: New dynamics between volume and volatility

Zhi Qiao, Zeyu Zheng, Joel Tenenbaum, Eugene Stanley and Baowen Li

National University of Singapore

Econophysics and econometrics agree that there is a correlation between volume and volatility in a time series. Using empirical data and their distributions, we further investigate this correlation and discover new ways that volatility and volume interact, particularly when the levels of both are high. We find that the distribution of the volume-conditional volatility is well fit by a power law function with an exponential cutoff. What's more, the volume-conditional volatility distribution scales with volume, and collapses these distributions to a single curve. We exploit the characteristics of the volume-volatility scatter plot to find a strong correlation between logarithmic volume and a quantity we define as local maximum volatility (LMV), which indicates the largest volatility observed in a given range of trading volumes. This finding supports our empirical analysis showing that volume is an excellent predictor of the maximum value of volatility for both same day and near future time periods. We also use a joint conditional probability that includes both volatility and volume to demonstrate that invoking both allows us to better predict the largest next day volatility than invoking either one alone. Thus a new dynamics between volume and volatility has been established which will greatly help people invest in the financial market knowing the possible largest risk to be.

P.20

Propagation of waves in stochastic memristors

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We consider the 'memory resistor' or memristor, a nonlinear electric circuit element whose resistance does not remain constant but depends on the history of the system. Its functionality is determined by the electrode-TMO (transition metal oxide) interface and the distribution of oxygen vacancies. We start with the one-dimensional lattice model by Rozenberg et. al. [1], in which the vacancies hop between the lattice sites depending on the external voltage and the local resistance is proportional to the number of vacancies. The corresponding master equation is formulated and by taking the continuum limit, we derive a generalized Burgers equation to interpret the dynamics of oxygen vacancies as nonlinear traveling waves. We show how these wave processes affect the electric properties of the device.

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P.21

Exact complexity: The spectral decomposition of intrinsic computation

Paul Riechers, James P Crutchfield and Christopher J Ellison

UC Davis

We give exact formulae for a wide family of complexity measures that capture the organization of hidden nonlinear processes. The spectral decomposition of operator-valued functions leads to closed-form expressions involving the full eigenvalue spectrum of the mixed-state presentation of a process's ϵ-machine causal-state dynamic. Measures include correlation functions, power spectra, past-future mutual information, transient and synchronization informations, and many others. As a result, a direct and complete analysis of intrinsic computation is now available for the temporal organization of finitary hidden Markov models and nonlinear dynamical systems with generating partitions and for the spatial organization in one-dimensional systems, including spin systems, cellular automata, and complex materials via chaotic crystallography.

P.22

Uncertainty in the Bifurcation diagram of cardiac action potential duration

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To understand the underlying mechanisms of cardiac arrhythmias, computational models are used to study heart rhythm dynamics. The parameters of these models carry inherent uncertainty. Therefore, to interpret the model output, uncertainty quantification (UQ) is important. Polynomial chaos (PC) is a computationally efficient UQ method in which a model output Y, dependent on some uncertain parameters represented by a random vector $\boldsymbol{\xi}$, is approximated as a spectral expansion in multidimensional orthogonal polynomials in $\boldsymbol{\xi}$ [1]. The expansion can then be used to characterize the uncertainty in Y.

We applied PC methods to UQ of the dynamics of a two-dimensional return-map model of cardiac action potential duration (APD) restitution in a paced single cell [2]. We considered uncertainty in four parameters of the model: three time constants and the pacing stimulus strength. The basic cycle length (BCL) (the period between stimuli) was treated as the control parameter. Model dynamics was characterized by the APD and stability of fixed points of the model at a range of BCLs, and by the BCLs at which bifurcations occur; we performed PC UQ for these model outputs. The results were summarized as a “probabilistic bifurcation diagram" that visualizes the location and stability of fixed points as uncertain quantities.

Classical PC methods assume that model outputs are continuous and reasonably smooth over the full domain of $\boldsymbol{\xi}$. Outputs of APD restitution models do not necessarily exist over the full domain of the uncertain model parameters; often they exist only on irregularly shaped subdomains. We therefore used a numerically-approximated Rosenblatt transformation to map each irregularly shaped subdomain onto a rectangular domain. PC representations of the outputs on the rectangular domains were then constructed [3]. Coefficients of the PC expansions were estimated using Bayesian inference methods.

To evaluate the performance of our PC method, PC UQ results were compared to Monte Carlo UQ results. Both methods gave similar results, but PC UQ (including Rosenblatt transformation and Bayesian inference) required less than 10 hours of computational time, compared to approximately 65 hours required for Monte Carlo sampling of the model outputs at 1×10^6 $\boldsymbol{\xi}$ points. Thus, our study demonstrates that PC methods are useful tools for evaluation of uncertainty in bifurcation diagrams.

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P.23

Phase synchronization of weakly coupled boolean oscillators

Damien Rontani, David P Rosin and Daniel J Gauthier

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We propose a new experimental realization of a periodic oscillator that we term Boolean phase oscillator (BPO) [1]. One of the important features of our design is that it allows us to tune the coupling strength using only Boolean signals. Our BPO is realized on a field-programmable gate array (FPGA) in its autonomous mode of operation. It consists of a ring oscillator with state-dependent delay taking two discrete values depending on an external coupling signal. We demonstrate experimentally and numerically that two uni- and bidirectionally coupled BPOs can exhibit phase synchronization. We characterize the synchronization regions as a function of the frequency detuning between two BPOs and a quantity related to the variation of state-dependent delay. We notice that the synchronization regions become larger when the second quantity is increased. This allows us to conclude that this quantity is an effective coupling strength in BPOs.

We gratefully acknowledge the financial support of the U.S. Army Research Office Grant W911NF12-1-0099 and National Science Foundation IGERT Grant DGE-1068871.

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P.24

Multi-resonance phenomena in a Hopfield neural network with two time delays

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A Hopfield neural network with random connection strengths and time delay demonstrates periodic, quasi-periodic, and chaotic behavior. In order to understand the mechanisms of different rhythm generation we investigated Hopfield neural networks with one and two time delays. The neurons in both neural networks are connected through inhibitory synapses (connections “all-with-all”) with the same connection strengths $a_{ij} = -c$ (i, j = 1, 2, . . . , 10), where c is varied from 0 to 5. The total number of neurons is equal to 10 in both one- and two-time-delayed networks. The neural network activities are described by ordinary differential equation and are solved by a modified 4th order Runge-Kutta method developed for differential equations with time delay. The initial conditions are set to very small random values. The neural networks demonstrate different activities as the connection strength and the values of time delay are varied. The neural network with one time delay shows usual behavior. These behaviors include saturation of oscillation amplitude and linear increase in oscillation period when the time delay τ increases from 0.1 to 10. In contrast, the neural network with two time delays demonstrates unusual multi-resonance activity. In the latter case, we varied time delay τ_1 for 5 neurons from 0.1 to 10, while the time delay for the other 5 neurons is kept constant ($\tau_2 = 10$). When τ_1 is increased, the amplitude of oscillations demonstrates multiple maxima at τ_1 = 0.7, 10, 15, and 29. In addition, the period of oscillation increases linearly at small delays of τ_1 from 0.1 to 0.5. At larger time delays the period of oscillations show multiple jumps at τ_1 = 0.7, 1.1, 1.9, and 4.5. Investigations of maps, Fourier spectra, correlation dimensions, and entropies of the neural network outputs provide insights into the development of different oscillation behaviors.

P.25

Effect of a competing scavenger on a predator-prey model with a Holling Type II functional response

Susmita Sadhu

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We consider a predator-prey model with a Holling Type II functional response and study the effect of a competing scavenger on the system. The scavenger feeds on the carcasses of the predator and predates the common prey, thus competing with the predator. Earlier studies have dealt with this system with Type I functional response. In our model, we take into account the competition between the predator and the scavenger, and consider a functional response of Holling Type II. We will find conditions on the parameters that will allow co-existence of the three species. Numerically we find evidence of existence of stable limit cycles and also period doubling orbits for a wide range of parameter values.

P.26

Dynamics of a laser diode as a feedback intensity detector

Aakash Sahai, Byung Chil Kim, Alexandre D. Locquet and David S. Citrin

Georgia Institute of Technology

In this paper we present some initial results on a new technique for sensing the the intensity of light reflected by a target by exploiting the dynamical changes induced by feeding back the reflected light into the laser cavity. We show using some preliminary experimental data that external optical feedback lowers the diode terminal voltage by measurable value with a certain trend. These results have applications to feedback detection for data storage such as in an optical drive and in data communications such as in on-off switching fiber-optic communications. Additionally the laser feedback-level detector can be applied to a variety of sensors. We try to analytically model the dynamics the laser diode upon the injection of an external optical feedback to explain the reduction in terminal voltage of a constant-current power supply. Preliminary simulation results are presented to support the observation of reduction in terminal voltage.

P.27

Revealing the state space of turbulent pipe flow by symmetry reduction

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Within the last decade, a framework to study turbulence has emerged that promises better understanding of chaotic dynamics. In this approach, equilibrium solutions of the Navier-Stokes equations are used to define dynamically-invariant and representation-independent coordinate systems onto which the dynamics of turbulent flows at moderate Reynolds number are projected. The resulting projections reveal how exact solutions shape turbulence: the observed coherent structures are the physical realizations of the flow's least unstable invariant solutions, with turbulent dynamics arising from a sequence of close visits to these solutions. However, continuous symmetries (e.g., translational and azimuthal symmetries relating families of physically equivalent states of a pipe flow) induce drifts that mask the underlying chaotic dynamics. In order for the 'shape-changing' dynamics of a turbulent flow be revealed, one must first quotient these symmetries. This is achieved using the 'method of slices' which exposes the skeleton underpinning chaotic dynamics and its state-space geometry. Visualizations of the flow within a symmetry-reduced slice and its linearization at equilibria enable the mapping of the unstable state space manifolds, determine close recurrences, identify connections between different invariant solutions, and determine relative periodic orbits that capture turbulent dynamics at transitional Reynolds numbers.

Only very recently has this approach has been applied to pipe flows [1]. The result is the first discovery of relative periodic orbits—structures embedded in turbulence thought to play a central role in shaping turbulence—for turbulent pipe flow. Here we report on our continued search for relative periodic orbits by identification of turbulent trajectory segments that are far apart in the full state space, but nearly recurrent within the symmetry-reduced slice.

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P.28

Nonlinear normal modes and quanta in the β Fermi-Pasta-Ulam lattice

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We enumerate simple periodic orbits for the well-known Fermi-Pasta-Ulam (FPU) problem. Using these solutions as simple modes for the problem, we construct quantum solutions of the corresponding problem. These studies present a natural generalization of the concept of phonon in the nonlinear realm. Phonon - a quantum of lattice vibration, finds its quantum description in terms of the wavefunctions of a harmonic oscillator [1]. The special structure of the Hamiltonian helps us to second-quantize it in terms of the creation and annihilation operators. In a rare instance, this notion has been extended where an additional inverse-square interaction can be added [2]. Of course, there are many instances when for a number of exactly-solvable systems and their Lie-algebraic generalizations, the operators can be written [3,4]. From a pedagogical point of view, the concept of phonon is well-explained in [5] by making a precise connection between the equations of motion of the normal coordinates for modes and the corresponding wavefunctions. By plotting various projections, the phonon wavefunction can be visualized. In this paper, we would have liked to present such a description for a nonlinear system. Since nonlinearity of the FPU Hamiltonian prevents us to make a one-to-one coordinate transformation between the coordinates of the particles and the modes, we shall restrict ourselves to the simplest modes that we have been able to enumerate. Using these, we will follow in spirit the usual discussion on phonons and attempt to present the quantum states built on the nonlinear normal modes.

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Water and preliminary liquid sodium results for the rapidly rotating 3 meter UMD geodynamo experiment

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Experimental results are presented from the three meter spherical-Couette geodynamo experiment, which is geometrically similar to the Earth's core. In the water-filled device, a systematic study of precession-forced flows and differential rotation rates is carried out. At high rotation rates in the precession forcing experiment, free shear layers are observed. Bi-stable behavior is found in the turbulent, rotating spherical Coutte flow within certain Rossby number ranges.

In recent liquid sodium experiments, a large number of distinct turbulent flows are observed in different ranges of the Rossby number. An intermittent dipole enhancement is observed when a strong magnetic field is applied with a specific Rossby number, which could be geodynamo-style feedback.

Additional turbulent states and greater field amplification might be found in unexplored parts of parameter space. Parts of parameter space that will be explored in future liquid sodium experiments include faster rotation rates, greater input power, and stronger or weaker applied magnetic fields.

P.30

Quantum tunneling and chaos in classical scale walkers

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We study the behavior of 'walkers'; small droplets bouncing on a fluid layer vibrated at amplitudes just below the onset of Faraday instability. It was shown recently that despite their macroscopic size, the droplet dynamics are stochastic in nature and reminiscent of the dual particle-wave dynamics in the realm of quantum mechanics [1]. We use these walkers to study how chaos, which is macroscopically unpredictable, will manifest in a quantum setting. Pecora showed in 2011 that tunneling for particles that have a chaotic ground state is different from tunneling for particles with a regular ground state [2]. In the experiment we gather data that illustrates the particle trajectory and tunneling behavior as particles transition across the barrier in the double well system with both integrable and chaotic shapes.

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P.31

KAM theory for quasi-periodic equilibria in 1D quasi-periodic media–II: long-range interactions

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We consider Frenkel-Kontorova models corresponding to 1 dimensional quasi-crystal with non-nearest neighbor and many body interactions. We formulate and prove a KAM type theorem which establishes the existence of quasi-periodic solutions.

The interactions we consider do not need to be of finite range or involve finitely many particles but have to decay sufficiently fast with respect to the distance of the position of the atoms. The KAM theorem we present has an a-posteriori format. We do not need to assume that the system is close to integrable. We just assume that there is an approximate solution for the functional equation which satisfies some non-degeneracy conditions.

P.32

Transition to turbulence in a Kolomogorov-like flow: A dynamical systems perspective

Balachandra Suri, Jeffrey Tithof, Radford Mitchell Jr, Ravi Pallantla, Roman O Grigoriev and Michael F Schatz

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Recent theoretical advances suggest that turbulence can be characterized using exact unstable solutions of the Navier Stokes equations, called Exact Coherent Structures (ECS). Due to their experimental accessibility and theoretical tractability, two-dimensional flows provide an ideal setting for the exploration of turbulence from a dynamical systems perspective. In our talk, we present a combined numerical and experimental study of electromagnetically driven flows in a shallow layer of electrolyte. Our experimental results include the sequence of bifurcations the flow undergoes en route to becoming weakly turbulent. We discuss the effects of boundaries on the flow structure. On the numerical front, we present results from a 2D DNS, comparing them with the experiment. Also, In the weakly turbulent simulation of the flow, we search for exact coherent structures and present a few we have identified.

P.33

The virus of my virus is my friend: modeling the ecological effects of virophage

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Virophages are viruses of viruses. Virophages are found across the globe and influence organismal systems involving algal blooms and human diseases. Virophages propagate by utilizing transcriptional machinery from another virus and, thus, must coinfect a mutual host. Coinfection is thought to occur primarily by two different means: either the virophage and virus entangle and the pair enter the host or the virus and virophage independently enter. We ask: how do these different modes of coinfection affect the ecological dynamics between host, virus, and virophage? To address this we construct two ODE models of poplation dynamics, one for each mode of coinfection. We statistically sample biologically relevant parameters to catalog existing dynamics by linear stability analysis. In both models, the virophage causes a reduction in viral densities and an increase in host densities. We find similarities between model dynamics such as the existence of stable coexistence and cycles. However, bistability is observed only in the model with independent entry of virophages. Altogether, our models shed light on ecological effects of virophage, irrespective of infection mode, and means by which certain population level measurements may provide additional information to identify the mode of coinfection outside of direct observation.

P.34

Describing chaotic dynamics in Rayleigh-Bénard convection using persistent homology theory

Jeffrey Tithof, Balachandra Suri, Samuel G Raben, Miroslav Kramar, Mu Xu, Mark Paul, Konstantin Mischaikow and Michael Schatz

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We employ a new technique for describing the dynamics of spatiotemporal chaos in Rayleigh-Bénard convection. We collect shadowgraph images of multiple time series of weakly chaotic flows, each starting from similar initial conditions which we impose using a laser. We then encode the topological characteristics of each frame into a so-called persistence diagram, measure the distance across all diagrams, and study the dynamical behavior. Results are compared to similar analyses of simulation data. This new methodology provides unique insight into the time evolution of this dynamical system and the chaotic evolution across separate runs, in both experiment and simulation.

P.35

Stationary alternating wave patterns in a reaction diffusion models

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We use an autonomous three-dimensional dynamical system to study embedded vortex structures that are observed to form in computational fluid dynamic simulations of patient-specific cerebral aneurysm geometries. These structures, described by a vortex which is enclosed within a larger vortex flowing in the opposite direction, are created and destroyed in phase space as fixed points undergo saddle-node bifurcations along vortex core lines. We illustrate how saddle-node bifurcations along vortex core lines also govern the formation and evolution of embedded vortices in cerebral aneurysms under variable inflow rates during the cardiac cycle.

P.36

Topological issues in nonlinear model reduction

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One method for model reduction for linear systems described by input-output differential relations is based on determining an internal state space model that balances the input to state and state to output properties in a precise way, by making the gramians of these descriptions equal and diagonal, and consequently deleting that part of the dynamics that does not contribute substantially to either measure. A generalization of these ideas to nonlinear dynamical systems has not been given to a satisfactory degree. One would expect a proper extension to be based upon three principles: 1) Balancing should be defined with respect to a nominal flow; 2) Only Gramians defined over small time intervals should be used in order to preserve the accuracy of the linear perturbation model and; 3) Linearization should commute with balancing. The first two principles lead to a definition of local balancing, but it is shown that an integrability condition generically provides an obstruction towards a notion of a globally balanced realization. However the information obtained by local balancing of a nonlinear system already provides useful information about the dominant dynamics of the system and the topology of the state space. To accomplish local balancing, two Riemannian metrics are specified: One models the local reachability and one models the local observability properties. In general these are incompatible, inducing a different global topology, thus explaining the aforementioned obstruction. Locally, it still may be possible to match these metrics: Local balancing at a point P corresponds to bending and reshaping the manifolds without tearing so that near P there is a snug fit (osculating contact) between the induced manifolds. Unlike the linear case, sensitivity and reduced modeling must be local concepts, and lead at best to a hybrid reduced model with modes of different dimension. Such multi-mode multi-dimensional systems (M3D) have recently been introduced. Finally, the use of stochastic reduced models will be mentioned, introducing a notion of uncertainty equivalence.

P.37

Mechanically induced synchronization of Mexican jumping beans

Andrea Welsh and Flavio H Fenton

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Mexican jumping beans, Laspeyresia salitans, seed pods a host tree which house larva of the moth Cydia Deshaisiana, move the seeds to a more optimal location for survival by hopping, rolling, shifting or flipping the seed from areas of higher temperatures to areas of lower temperatures. By characterizing their jumping pattern as periodic and coupling them through string, we seek to synchronize their motions experimentally. We relate the synchronization behavior of the beans to the Kuramoto model with different topology by adapting it with frequency modulated oscillators to account for the beans' atypical jumping behavior.

P.38

Dynamical state change detection and classification in EEG data from healthy individuals and Parkinson's patients

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While much of the underlying cellular and molecular pathology of chronic neurodegenerative disease, e.g. Parkinson's Disease, is well understood, comparatively little is known about the neurological processing changes that ultimately result in cognitive and physical disabilities. Intuitively, chronic neurological disease would be expected to have acute and chronic underlying dynamical states that are significantly different from healthy, age-matched controls. Furthermore, the timescales of state changes during cognitive processing would be expected to vary dramatically between pathological and healthy subjects.

We propose a Delay Differential Equation (DDE) - Singular Value (SV) method that utilizes the SVs of DDE features to detect and classify state changes in dynamical systems or real world data. The method's utility is first shown by integrating the Rössler system while monotonically varying different bifurcation parameters found in the system and using the DDE-SV method to qualitatively observe the switch between chaotic and simple states. The experiment is performed in noisy regimes with signal-to-noise ratios (SNRs) ranging 30-0 dB in order to best simulate real data conditions. Next, the method is applied to EEG obtained during an auditory cued reaching and grasping paradigm where 9 Parkinsonian subjects, on and off medication, and 9 age-matched healthy controls attempted to reach for and grasp a virtual object with visual and sensory feedback provided throughout the task. We use singular value decomposition (SVD) on features obtained with DDEs to classify state changes in the EEG data. Each subject performed fifty trials resulting in either success or failure depending on the individual's ability to grasp the object. The complex task provided many opportunities for the subject to perform differential cognitive processing and neurological state changes, e.g. auditory tone, movement onset, success or failure to grasp the object. Finally, we show the ability to classify each state first within a subject and then use this information to differentiate between Parkinsonian and healthy control subjects based solely on raw EEG data.

P.39

Stationary and traveling chimera states in a phase-coupled oscillator system with nonlocal coupling

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Networks of coupled oscillators have been studied extensively because of their wide range of applications in physics, chemistry, and biology. When the coupling is weak, phase reduction leads to a simplified description of the dynamics. Among the phase-coupled models that result, Kuramoto-type models are the most well-known. Numerous studies with either local or global coupling have been made, but nonlocal coupling remains poorly understood. In 2002, Kuramoto et al. investigated the system

$$\frac{\partial \theta}{\partial t} = \omega - \int G(x-y)\sin[\theta(x,t) - \theta(y,t) + \alpha]dy \qquad \text{(P.39.1)}$$

and found a solution consisting of a group of coherent, phased-locked oscillators in a background of incoherent oscillators [1], later referred to as the chimera state [2]. These states usually coexist with a stable fully synchronized state and are therefore hard to find. Here, we propose a *nonlocal* phase-coupled model in which chimera states can be found easily. By adjusting the parameters of the model, we can control the number of coherent clusters. In addition, a traveling chimera state can also be observed in this model.

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P.40

Chaos, stirred not shaken

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Analytic and experimental studies have focused on the identification of key signatures to serve as structural invariants in system with complex dynamics. Such invariants would allow dynamically similar systems with chaotic dynamics from diverse origins to be united into a single class. Among these key structures are various homoclinic and heteroclinic bifurcations of low codimensions that are the heart of the understanding of complex behaviors because of their roles as organizing centers of dynamics in parameterized dynamical systems.

A new computational technique based on the symbolic description utilizing kneading invariants is proposed for explorations of systems with chaotic attractors. It allows for uncovering the stunning complexity, self-similarity and universality of the fractal swirl-like patterns and detects the organizing centers - codimension-two T-points in the parameter space of such systems, which are induced by hetero- and homoclinic bifurcations of saddle equilibria in the phase space.

The technique has been successfully tested on several exemplary systems, including the classical Lorenz equation, 3D normal forms from mathematics, and models from nonlinear optics and electrical circuits.

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P.41

Locomotion and scattering in heterogeneous environments

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We present an overview of our studies of the dynamics of animals and robots running on heterogeneous granular media in both laboratory experiment and theory/simulation. We previously studied the mechanics of locomotors on and within homogeneous granular media (substrates composed of collections of similar sized particles). To model locomotion in these substrates, which lack comprehensive governing equations, we developed an experimentally validated multi-particle simulation and an empirical granular resistive force theory to predict locomotion performance in swimming [1] and running [2]. We now seek to understand how locomotion is affected when granular environments are composed of a large distribution of particle sizes. We begin by considering the case in which particles are widely separated in scale—we can then treat the substrate as a homogeneous terrain described by a continuum approach plus localized scatterers (e.g. larger "boulders") whose sizes are comparable to a characteristic scale of the locomotor. We ask questions about various aspect of locomotion in this system: How should a running animal/robot control its self-deformation to achieve high performance (speed, stability)? Does it need to plan for every interaction? How important are passive mechanical aspects of feet and limbs?

In our biological experiments, we observe the zebra-tailed lizard (*Callisaurus draconoides*) running on a granular bed of slightly polydisperse, 0.3 mm diameter glass particles. Larger particles ($\sim$2.54 cm diameter glass spheres or $\sim$3.8 cm 3D printed spheres) are placed on top of the bed in a lattice or random pattern. Locomotion kinematics of the lizard are recorded using high speed cameras, with and without the scatterers. Preliminary data shows that unlike thelizard's typical quadrupedal locomotion using a diagonal gait, when scatterers are present the lizard tends to use a bipedal gait, with a raised center of mass (CoM). We propose that the kinematics of bipedal running, in conjunction with the lizard's long toes and compliant hind foot [3], are the keys to this lizard's successful locomotion in the presence of such obstacles.

In robotic experiments we run a hexapedal robot, Xplorer ($\sim$15 cm in length, $\sim$100 g in mass) over a single boulder placed on a substrate of homogeneous, loosely packed poppy seeds. During locomotion, when the robot contacts the boulder with a part of its body, shafts or legs, the robot's direction of motion can change. To measure this scattering function for a single boulder, we systematically vary the perpendicular distance between the center of the boulder and the trajectory of the robot's center of mass (CoM) before collision (the impact parameter). For a fixed impact parameter, the angle at which the CoM deflects after leaving the collision site also depend sensitively on the contact point on the boulder and the rotation phase of the robot's legs. Counter-intuitively, the interactions are largely attractive such that the robot turns towards the scattering center.

To gain insight into the scattering dynamics, we also study a single boulder scattering problem in a reduced order model. The robot system with 6 CoM degrees of freedom and one additional leg rotation phase has a total dimension of 14 (7 general coordinates and their corresponding velocities). However, if exact collision dynamics are not a concern, the heavy boulder does not move during interaction, and the only quantity of interest is the scattering angle, we can reduce the dimension of the system. The deflection angle of the robot with rotational symmetry is treated only as a function of the impact parameter, with the effect of leg phase, contact point and all other degrees of freedom encoded as fluctuations added to the deterministic scattering. In addition, since the single boulder configuration has a continuous rotational symmetry, we can model the scattering region as a circle centered at the boulder. Such a system can be extended to a field of boulders in a lattice configuration (e.g. a hexagonal lattice). In this way we create a variation of the Lorentz gas problem (instead of bouncing, we have a soft "potential"). The deflection function measured in the experiment can be transformed to a 2-D Poincaré return map using natural variables (e.g. the angle of moving direction and the position on the boundary of the hexagonal cell) when we wrap the CoM trajectory into the elementary cell using proper group action. Periodic and running orbits in the soft billiard system are analyzed, and theories of deterministic diffusion and the dynamic zeta functions are applied to analyze the diffusion matrix in the full space.

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P.42

Parameter estimation and missing data recovery in electronic communications

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The dynamics of communication within complex social networks are receiving increasing attention in research and media. It is well established that patterns of human interaction are "bursty"; that is, they are well clustered in time in comparison to a Poisson process. We model these dynamics with self-exciting point processes and demonstrate how to fit the processes' parameters to data. We then consider a missing data problem: Given an incomplete record of communications, can we recover the missing information? For example, who sent or received an email for which we have only a time stamp? Using ideas that were used recently to study patterns in crime data, we present a method relying on the burstiness of the interaction dynamics. Testing this method on a data set of email traffic, we are able to guess the sender and receiver correctly a high proportion of the time, even when we are missing much of the data, with rich implications for security and surveillance.

P.43

Mathematical modeling of tumor growth

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Mathematical modeling of tumor growth is a well developed field, however, the inability to constrain model parameters in the context of a specific tumor limits the predictive power of models in cancer biology experiments and in clinical practice. We hypothesize that noninvasive imaging technologies, such as diffusion weighted MRI, can be used to extract tumor parameters from an early sequence of scans. With these parameters in hand, the model can be run forward in time and compared to subsequent tumor development, closing the model and experiment feedback loop essential to refinement and validation of models. In this work we use simulated data to determine the frequency and number of scans needed to reliably extract tumor growth parameters from noisy MRI data. We develop the methodology in the context of a clinically relevant problem of identifying cell populations resistant to targeted therapy.